# *Neutrino Detectors:*
Current Techniques, Future Challenges

CHRIS WALTER, DUKE UNIVERSITY

The intensity frontier offers a unique path to the heart of 21st-century particle physics. Fermilab will play a leading role in putting advanced accelerator and detector technologies to work for intensity-frontier experiments.

Lectures at Fermilab throughout 2009 will address topics including neutrino physics, muon physics, hadron physics and innovative accelerator and detector technologies for the intensity frontier.

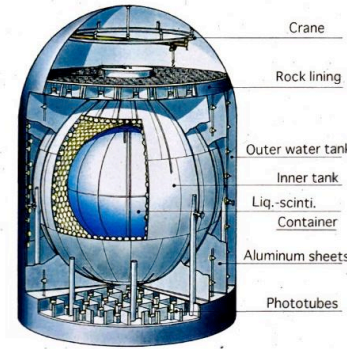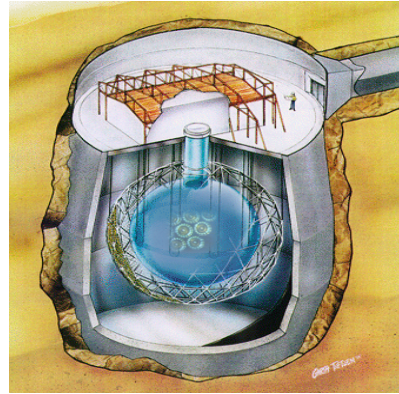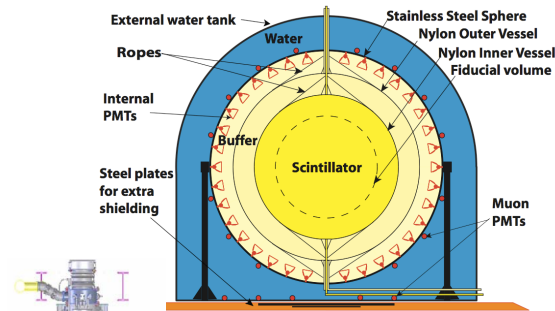Lectures will be held at Fermilab's Wilson Hall, One West. A reception will follow each lecture.
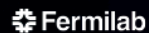
Fermilab • U.S. DEPARTMENT OF ENERGY • www.fnal.gov/ExtremeBeam

A Fermilab lecture series on Physics at the Intensity Frontier throughout 2009

extreme BEAM

Fermi National Accelerator Laboratory
Thursday May 7th 2009
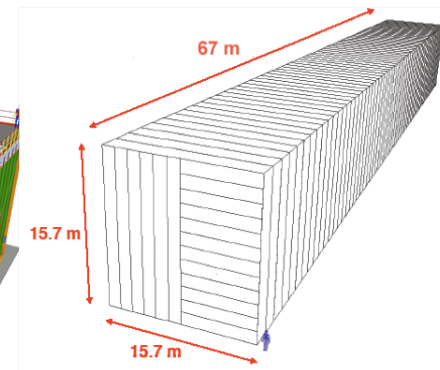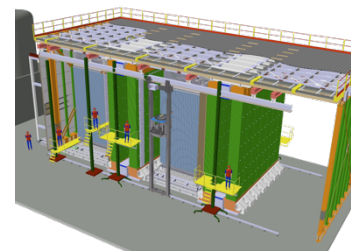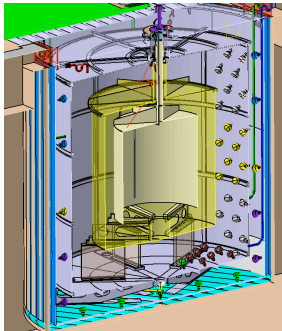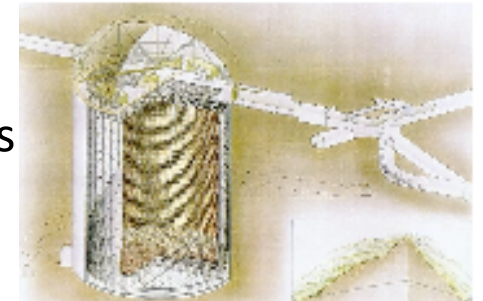
Types of neutrino experiments

Direct Mass * Double Beta Decay

Reactor Experiments * Atmospheric and Solar Neutrinos

<u>Accelerator Based Oscillation Experiments</u>

Today

Neutrino Detectors: The Facts of Life

Rate = Flux(E) * x-section(E) * Target

Make it big!   *It's really small.*
Sometimes not well known!

Concrete Example: Atmospheric neutrinos
(~ 1 GeV neutrinos on water nucleons in Super-K)

$$\frac{1}{cm^2 sec} \times \frac{6 \times 10^{-38}\ cm^2\ interactions}{nucleon} \times \frac{6 \times 10^{32}\ nucleons}{kton} \times \frac{86400 sec}{day} \times 22.5\ kton \sim \frac{10\ interactions}{day}$$

Physics Topics
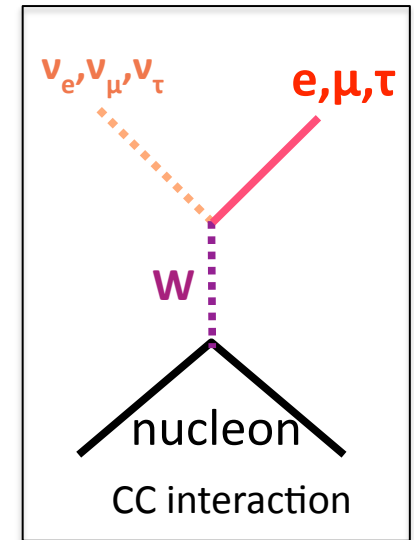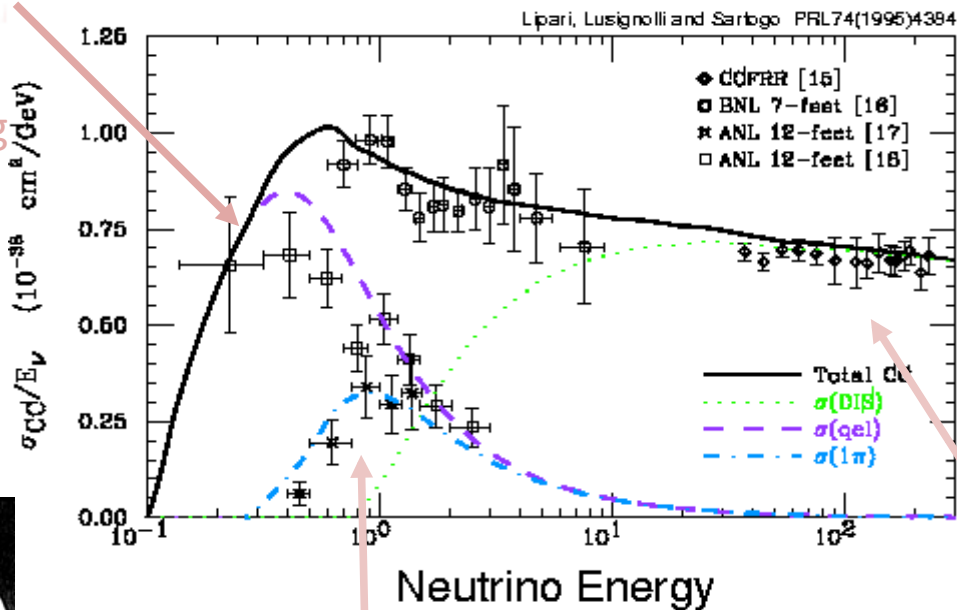*For giant underground*
Detectors:

- *Beam oscillation physics*
- *Proton decay*
- *Supernovae prompt + relic neutrinos*

How can we optimize for each of these topics?
What are the detector requirements?

# Neutrino x-sections (a topic of their own!)

More energy: More Particles!

Quasi-Elastic Scattering
(E <~ GeV)

ν_e, ν_μ, ν_τ

e, μ, τ

W

nucleon

CC interaction

Lipari, Lusignolli and Sartogo PRL74(1995)4384

◆ CCFRR [15]
▫ BNL 7-feet [16]
✳ ANL 12-feet [17]
□ ANL 12-feet [18]

— Total C
····· σ(DIS)
- - - σ(qel)
-·-·- σ(1π)

Neutrino Energy

$\sigma_{CC}/E_\nu \quad (10^{-38} \ cm^2/GeV)$

CHECK OUT NUINT!
CHECK OUT MINERVA!

DEEP SEA DAVE says—

CODDIES- the fish
cakes with oceans of flavor
ORPHANAGE
of cast-off mascots

pion muon

ν_μ

proton

Single Pion Production
E ~ GeV

muon

ν_μ

hadrons:
$p, n, \pi, K \ldots$

Multi-Pion Production +
Deep inelastic scattering
E > many GeV

MINOS / Magnetized Tracking

Scintillator strip
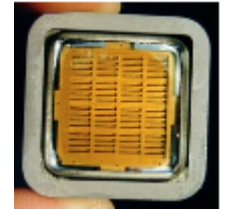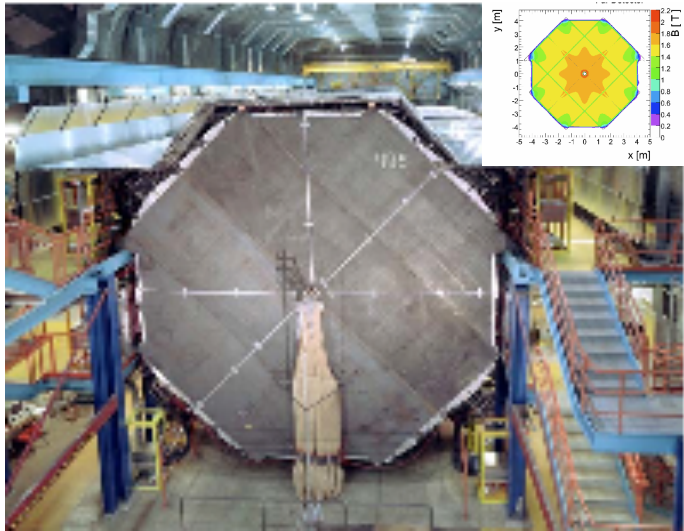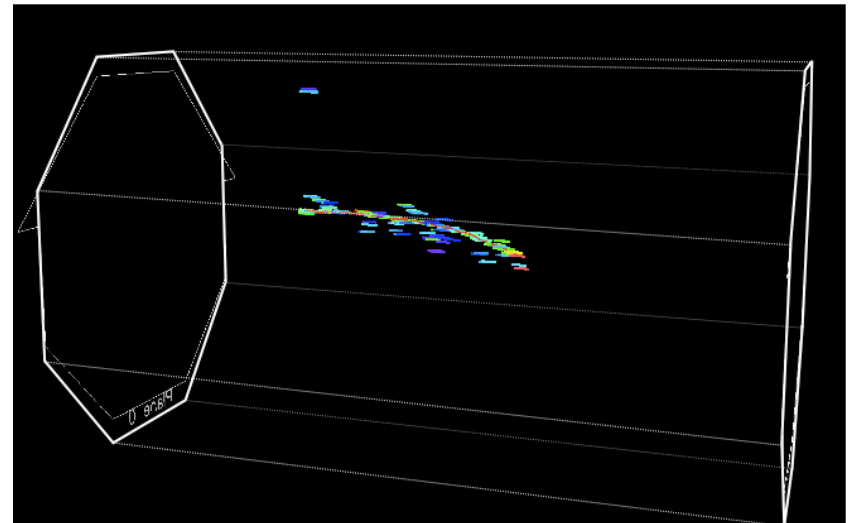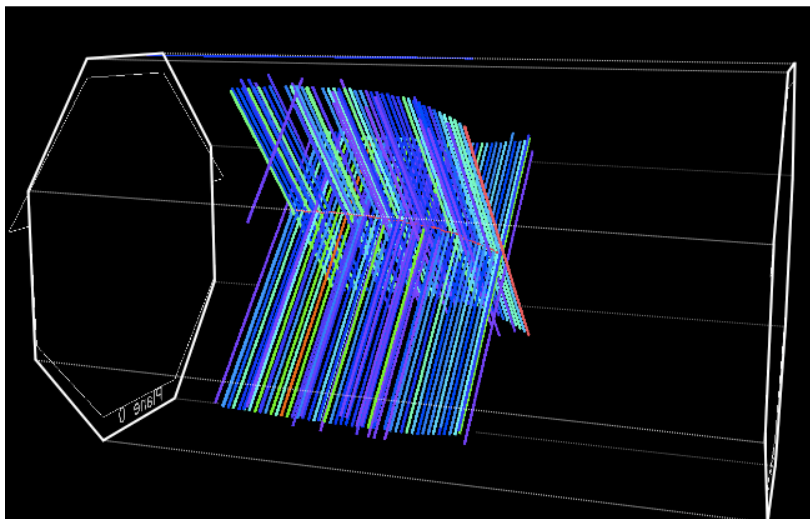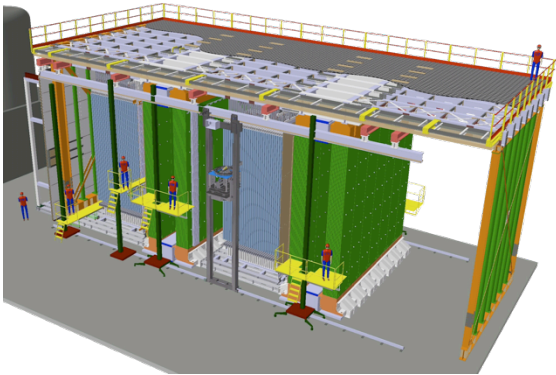
M16 PMT

Magnetized steel and scintillator Tracking calorimeter.

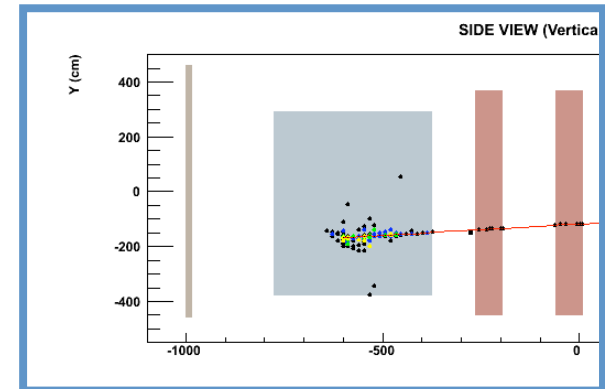2.5 cm steel, 1.3T field
4.1x1 cm extruded scintillator
With WLS fiber.
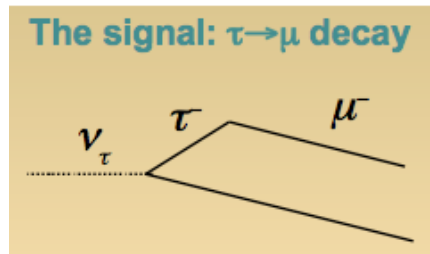
OPERA Nuclear Emulsion
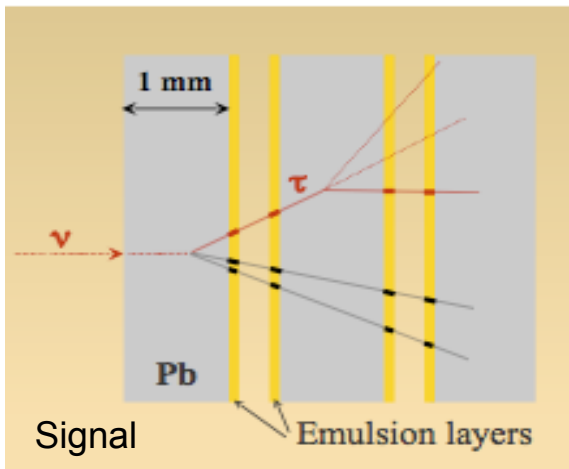

Uses ECC (Emulsion Cloud Chamber)
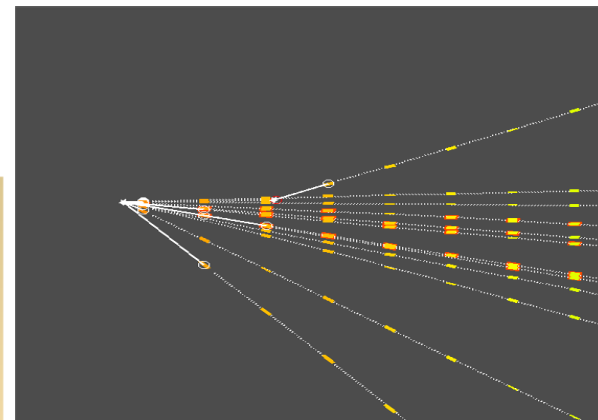**With automatic scanning**
+ Magnetic spectrometer.

After 1.5 years
Block installation done.

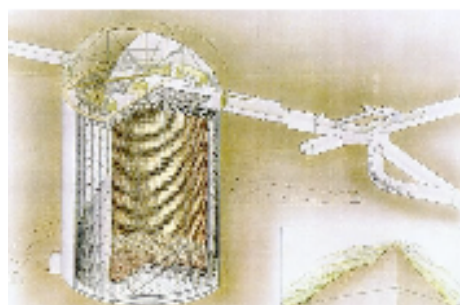Electronic trackers point
Back to bricks.

Signal

…a charm candidate!

The signal: τ→µ decay

T2K / Water Cherenkov

Non Segmented water Cherenkov Detector. No B field.

Magnet carriage installation

Far detector: Super-K

On and off-axis hybrid near detectors

ECAL   TPCs   FGDs

Magnet yoke

Magnet coils

ν beam

Pi-zero Detector   Tracker

ν_eCC

BG NC
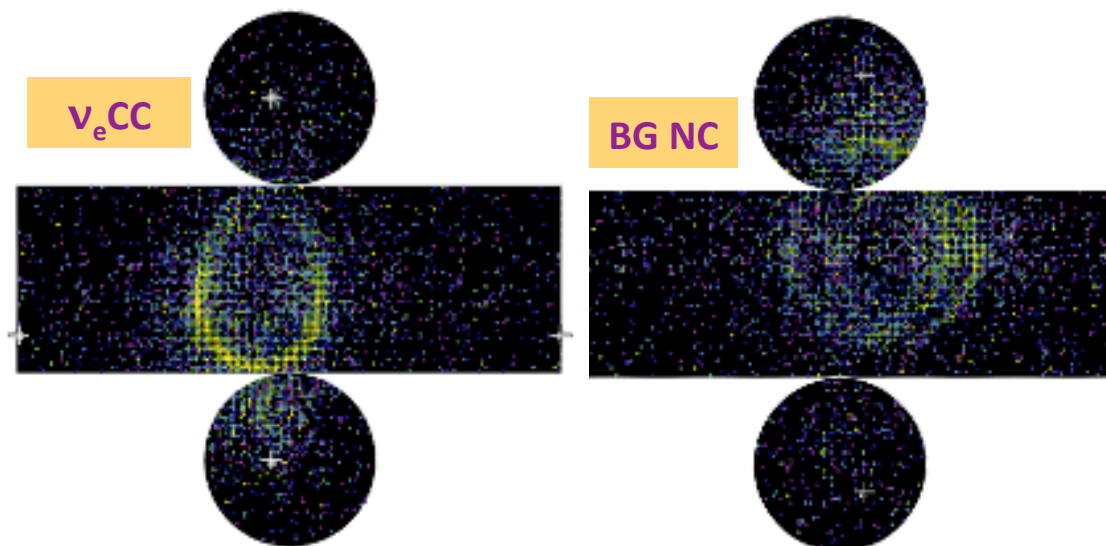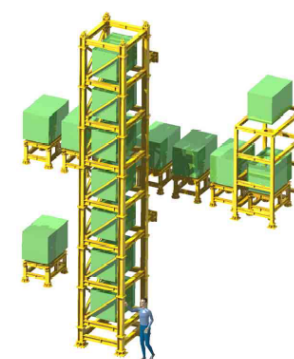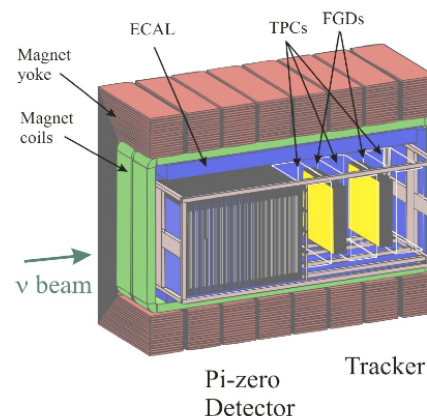
‣ 50 Kton Water Chernkov Detector

‣ >11,000 PMTs read out by QTCs

‣ Image processing for reconstruction

Nova – Low Z calorimeter

- 15 kton "totally active" **liquid** scintillator detector

Low Z tracking calorimeter: tracking + allow time for photons to convert and showers to develop.

Low Z calorimeter
(near and far detectors)
No B field.

To 1 APD pixel

67 m

15.7 m

15.7 m
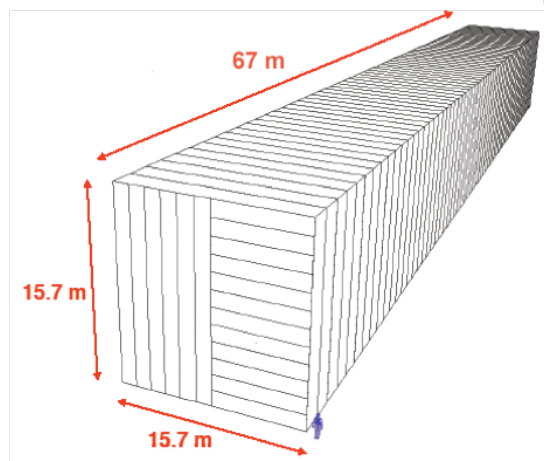
V v events
215 tons
of 20 tons

Muon Catcher
Containment
Fiducial
Veto

$2\ GeV\ \nu_e$

$\nu_e CC$

BG NC
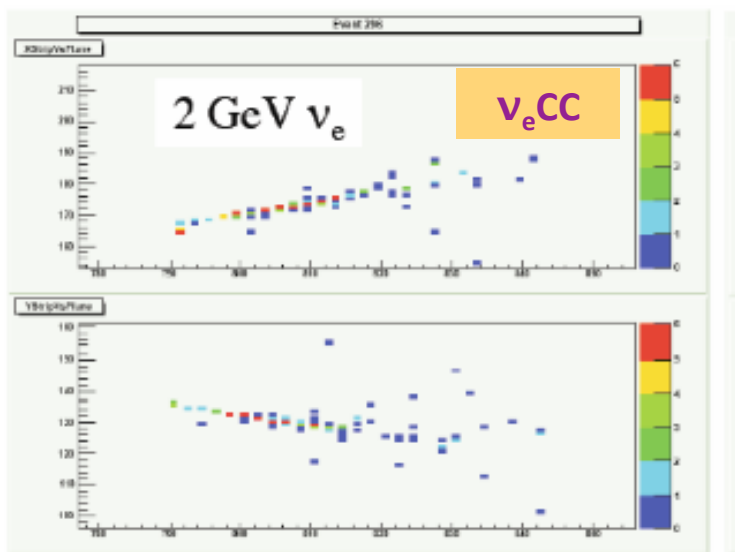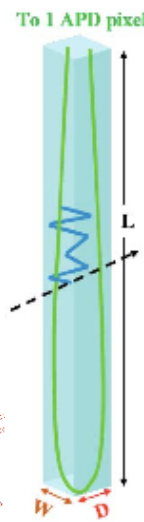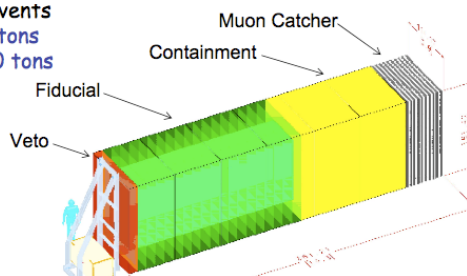
Scintillation/Hybrid Detectors

Minerva
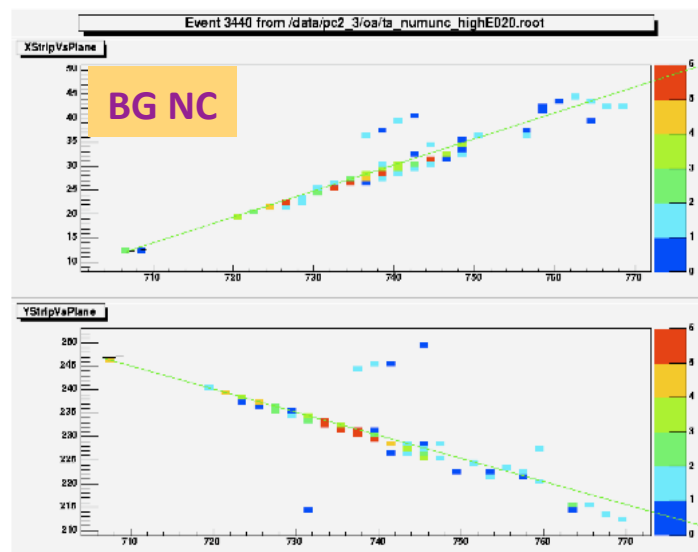
Scibar

MC

proton   muon

X-view   PE

strip

run: 294/6
event: 319   Data

vertex

K2K Fine-Grained Detector (Side View)
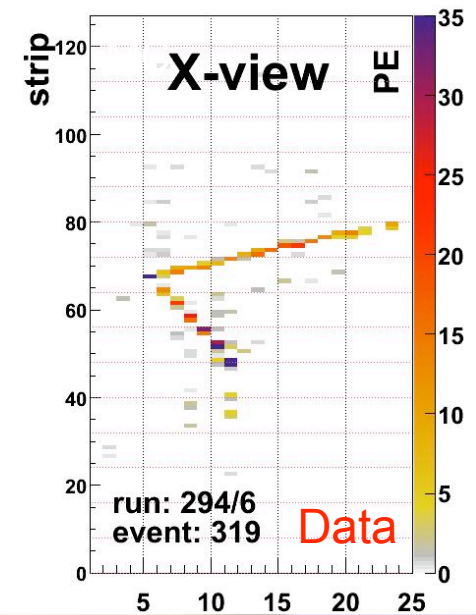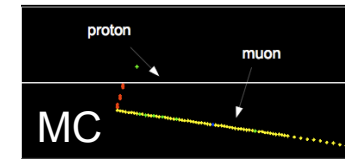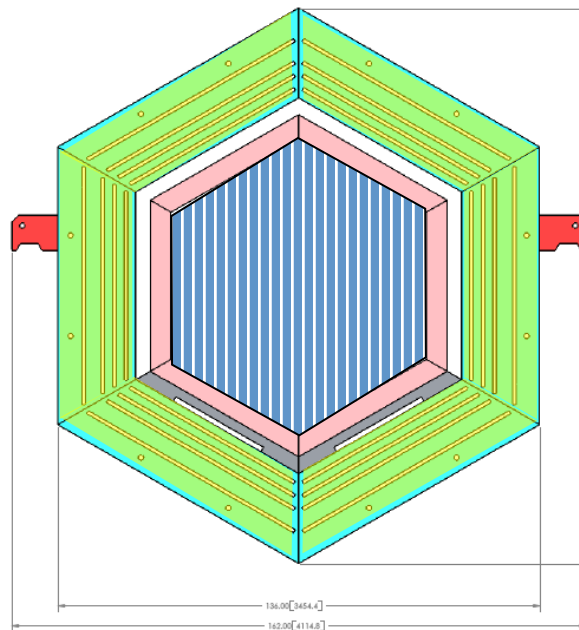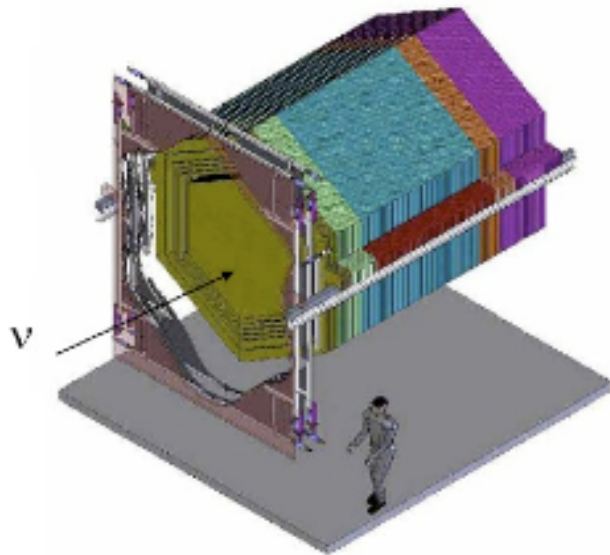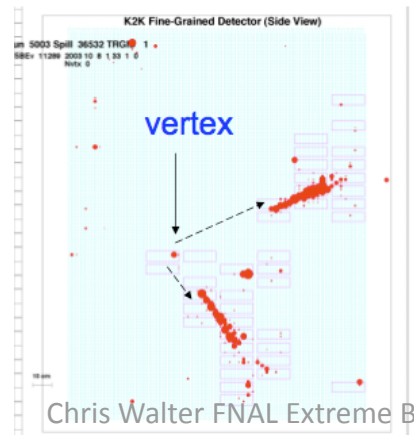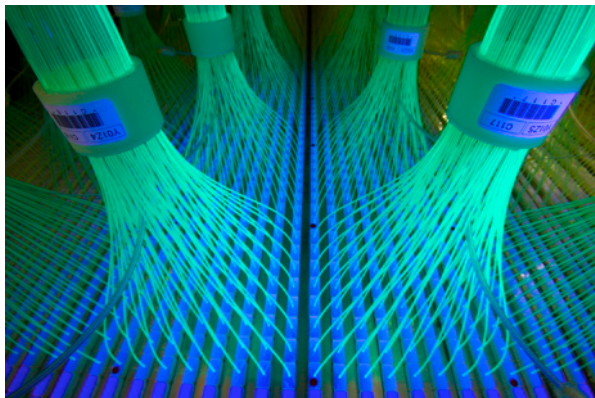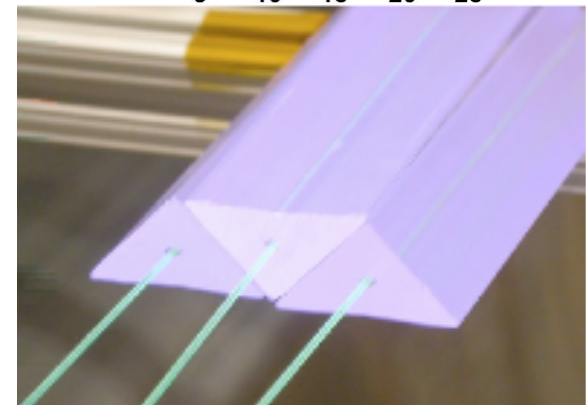
Read out by M64

Same Particles: Different Detectors

E. KEARNS – NPSS07

LIQUID ARGON
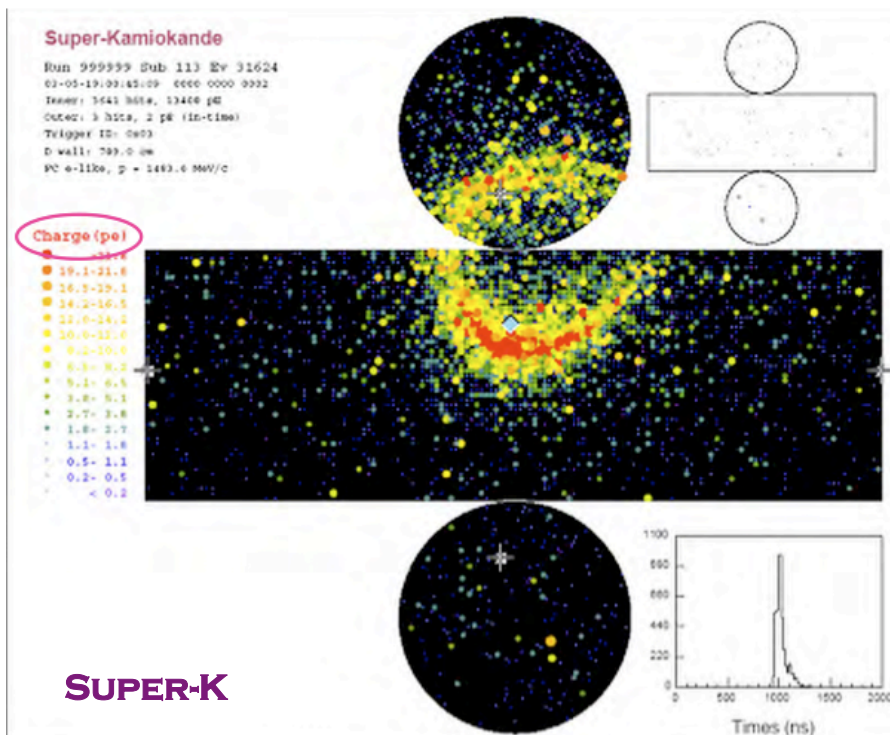
SUPER-K

NOVA

Monte Carlo Vectors	
proton	691 MeV/c
pi0	1442 MeV/c
gamma	245 MeV/c
gamma	1204 MeV/c

Chris Walter FNAL Extreme Beam Lecture

10

Project-X to DUSEL (LBNE)

8 GeV extraction
1 second x 2.25 x 10^{14} protons/1.4 sec
200 kW

120 GeV fast extraction spill
1.5 x 10^{14} protons/1.4 sec
2 MW

Recycler
3 linac pulses/fill

Stripping Foil

Main Injector
1.4 sec cycle

8 GeV H⁻ Linac
9mA x 1 msec x 5 Hz

Single turn
transfer @ 8
GeV

0.6 GeV
Front End
Linac

0.6-8 GeV ILC
Style Linac

PROJECT-X

$\nu + \bar{\nu}$, $\Delta m_{31}^2 > 0$
30+30 10^{20} PoT

× true value
— 68% CL
— 95% CL

LET'S MEASURE CP VIOLATION!

δ_{CP} ... $\sin^2 2\theta_{13}$

DUSEL Deep Underground Science and Engineering Laboratory **at Homestake, SD**

6 ½ Empire State Buildings for scale

Engineering
Geoscience
Physics
Astrophysics
Biology

Shallow Lab
Mid-level
Deep Campus
Open cut

Later Dirty Campus
Early Clean Campus
3M Detector array
Early Dirty Campus
Later Clean Campus

WATER CHERENKOV AND/OR LIQUID ARGON HERE AT 4850FT.

the Beam Lecture 11

Measuring CP Violation and Hierarchy
Schematic figures

Measure the electron appearance probability on top of a background

Do this with both a neutrino and Anti-neutrino beam.

Inverted Hierarchy

Normal Hierarchy
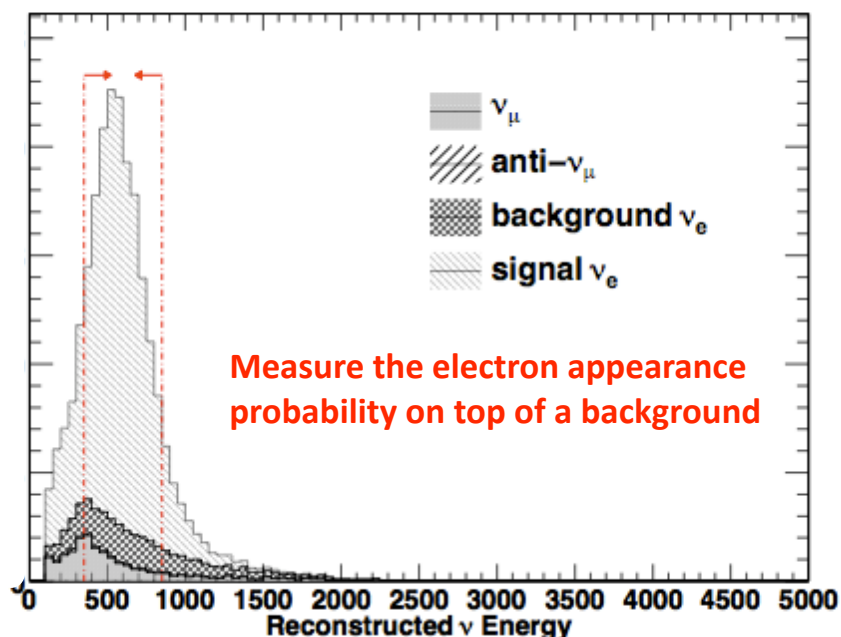
For appearance three main types of background:
intrinsic v_e, misidentified π^0, mis-identified charged μ

In DUSEL project we want a really high intensity beam and large mass > 100kton to get a good event rate. We need to measure the electron appearance probability in **both** neutrino and anti-neutrino beams.
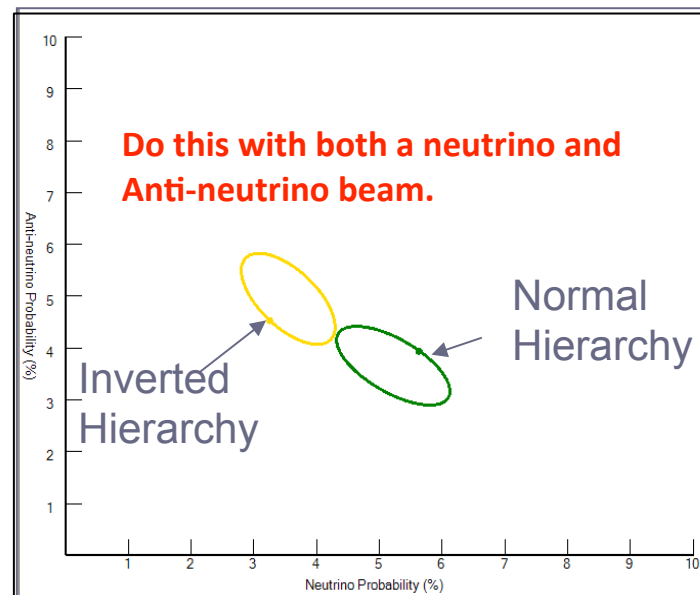
Changing CP moves you around the circles.

- Use Project-X
- We know how to build large WC detectors for "cheap".
- If we can figure out Liquid Argon holds the out the possibility of extremely good granularity and background rejection.

Examples of these Backgrounds in WC

Intrinsic ν_e contamination	$\pi^+ \rightarrow \mu^+ \nu_\mu$ $K^+ \rightarrow \pi^0 e^+ \nu_e$ $K_L^0 \rightarrow \pi^+ e^- \nu_e$ $\quad\quad \rightarrow e^+ \bar{\nu}_\mu \nu_e$ **DECAY PIPE**
Confuse $\pi^0 \rightarrow \gamma\gamma$ with ν_e	
Confuse ν_μ with ν_e	MUON NEUTRINO muon ELECTRON NEUTRINO electron shower
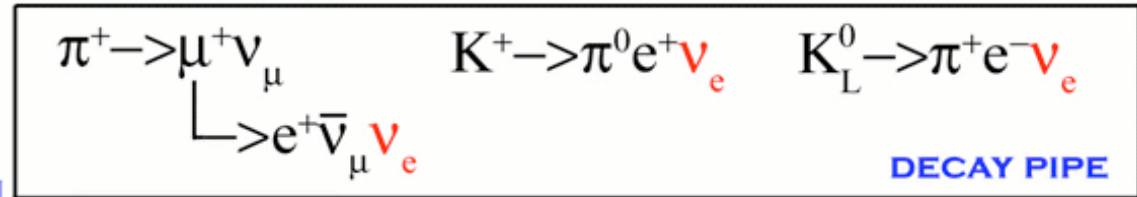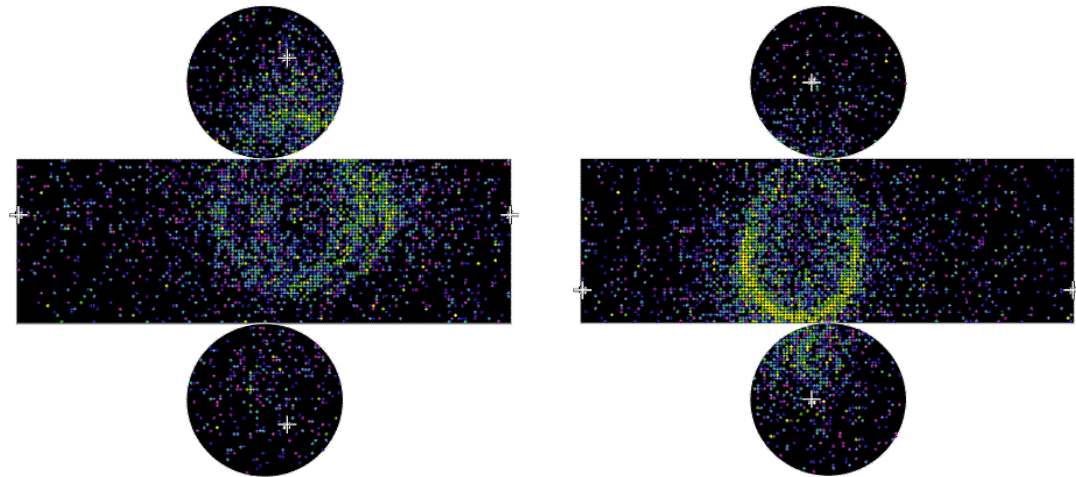
Cherenkov Radiation

Cherenkov light is emitted when a charged particle, like a muon or an electron goes faster than the speed of light in some medium. The Cherenkov light is emitted like a shockwave, in a cone along the direction of particle motion.
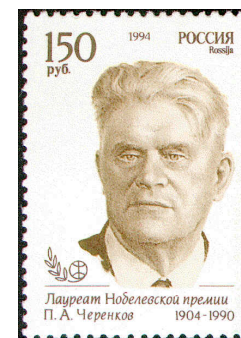
Hypersonic Jet
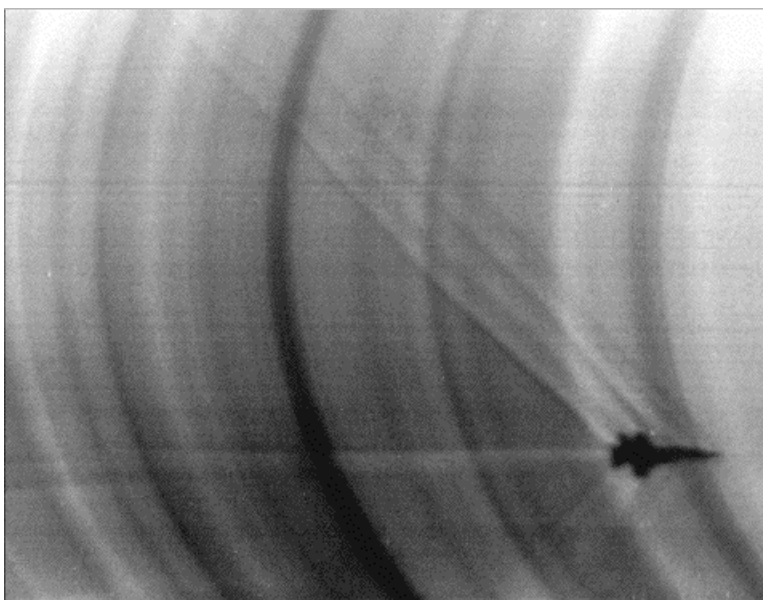
Moving faster than the speed of sound in air makes a sonic boom.

Reactor Core

Electrons moving faster than c/n in water make light.

Super-K

Particles **moving faster than c/n** make cones of light.

Chris Walter FNAL Extreme Beam Lecture

E$_\nu$ Reconstruction (assuming QE)

SUPERKAMIOKANDE   INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos(\theta_\mu)}$$
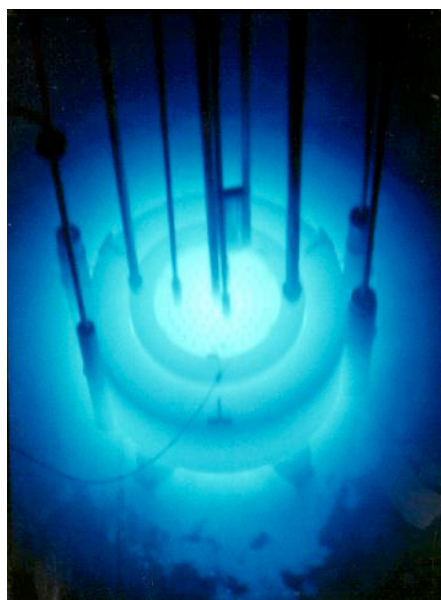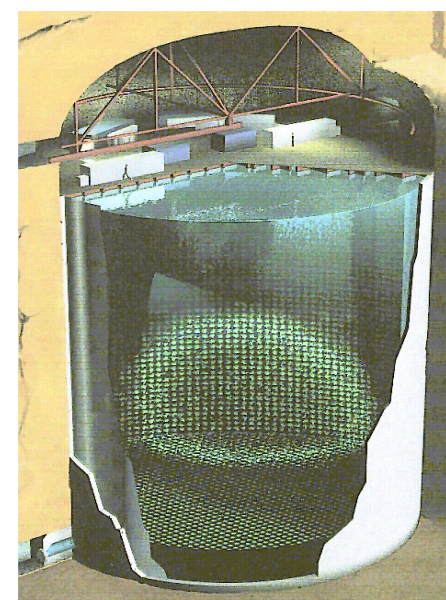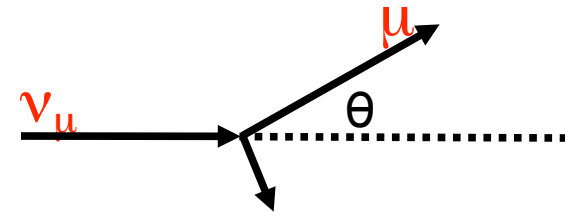
$m_N =$ Neutron Mass
$E_\mu =$ Muon Energy
$m_\mu =$ Muon mass
$p_\mu =$ Muon momentum
$\theta_\mu =$ Muon angle wrt beam
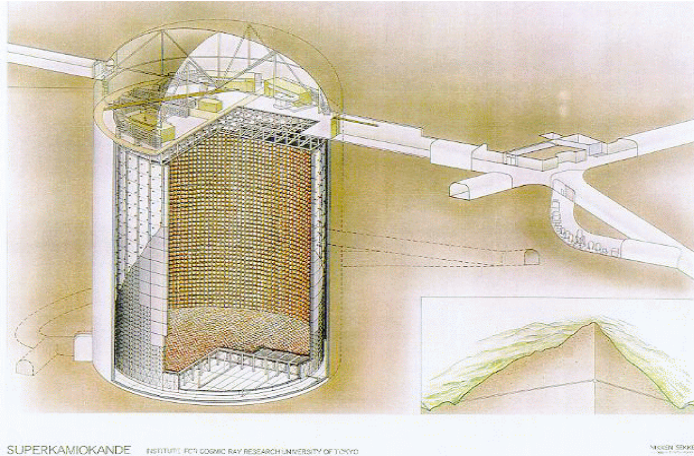
In Water Cherenkov detectors not every
particle is above Cherenkov threshold. Luckily,
in a Quasi-Elastic reaction, even if <u>only the muon</u> is visible
we can reconstruct the neutrino energy!
 [Case for most events in K2K/T2K Energies]

If the interaction is non Quasi-Elastic then the
reconstructed energy will be incorrect. Challenge:
In LBNE the energies are higher. [More later]

Ring Counting

Unequal size close peaks can be difficult to deal with.

Also handles ring fragments!

Telling Electrons from Muons
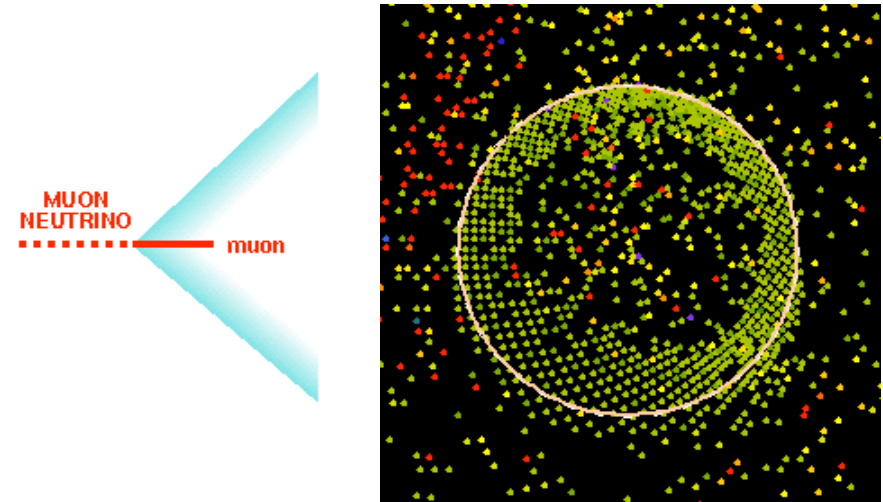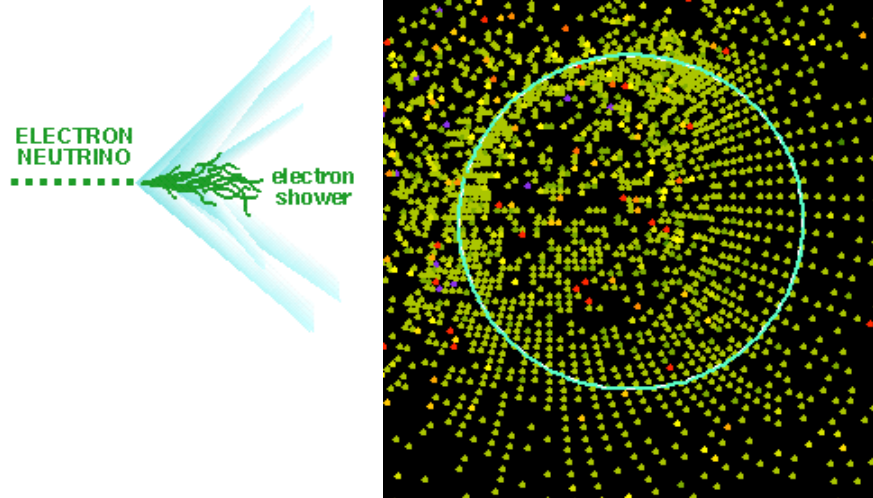
Compare profile of ring against a shape likelihood.
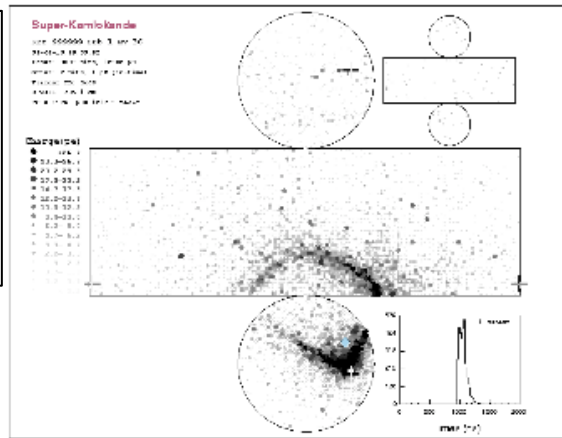
Electrons bremstrahlung and pair produce making many particles each making light.
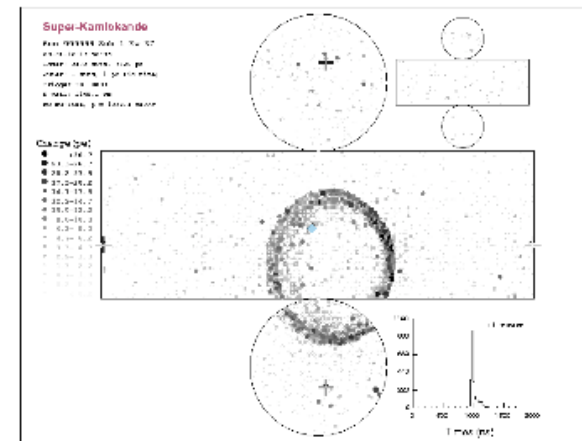
Thickness gives momentum
Muons move forward producing a single cone of light.

Pattern of Light Fitter

Optimized to find weak 2nd ring from asymmetric decay

- Start from single e-like ring with no decay electrons.

- Assume there is a 2nd ring from a pizero decay somewhere in the event.

- Make a e-like pattern (including scattered light) and move it around until you get the best fit.

- Check the invariant mass of the reconstructed pizero and likelihood and decide whether there was a ring or not.

ex.) 500MeV/c π^0
true $P\gamma_2$ = 55.5MeV/c
rec.Mπ^0 =140.4MeV/c^2
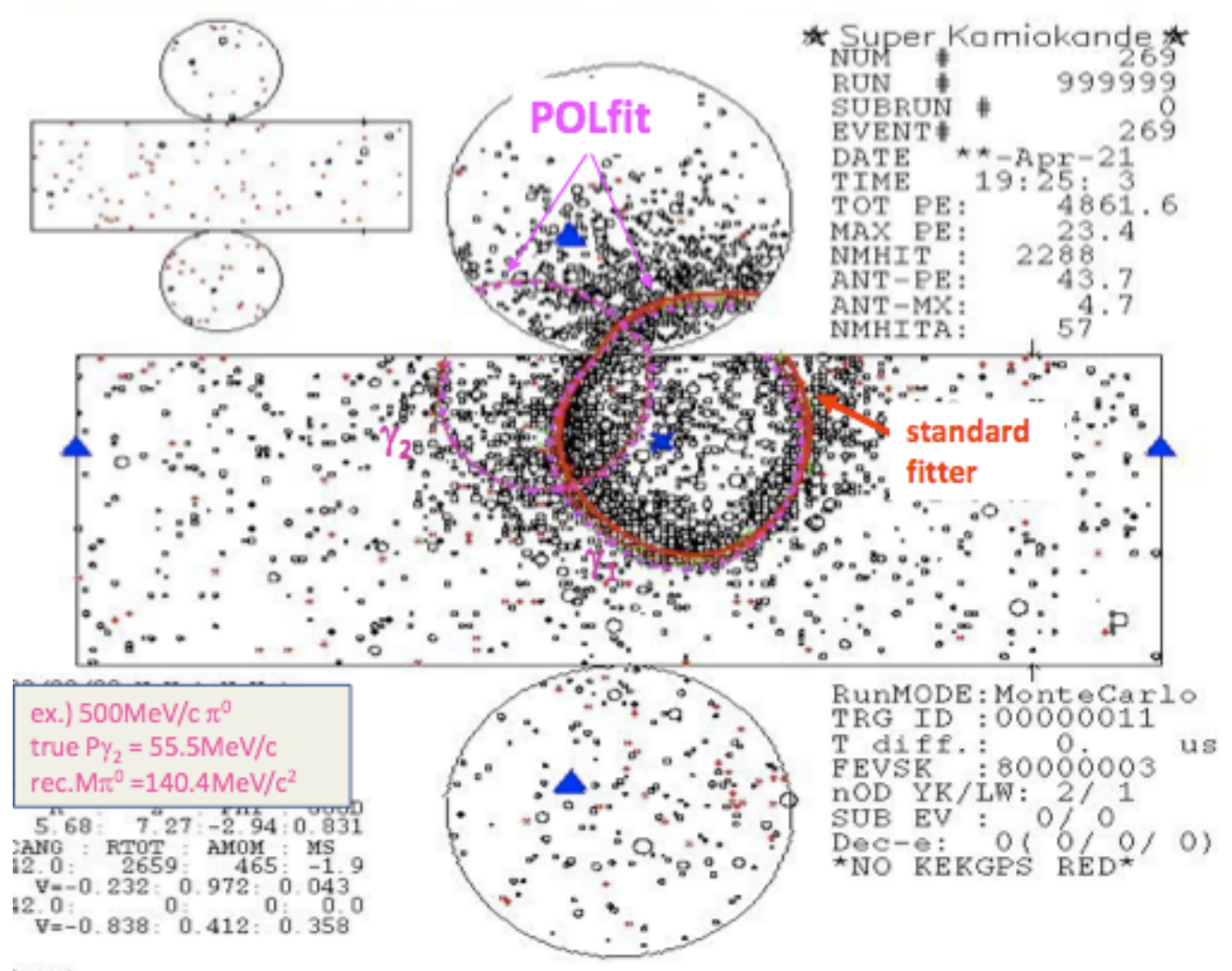
What happens at DUSEL energies?

Final efficiency   (Fannie Dufour)

Precuts efficiency:

E_{true} (GeV)	0-0.35	0.35-0.85	0.85-1.5	1.5-2.0	2.0-3.0
ν_μ CC Precuts eff:	nan	0.5%	0.6%	0.8%	0.9%
NC Precuts eff:	20%	26%	26%	22%	18%
ν_e Precuts eff:	94%	80%	61%	46%	36%

Fraction of QE is smaller at higher energy

Likelihood efficiency:

E_{rec} (GeV)	0-0.35	0.35-0.85	0.85-1.5	1.5-2.0	2.0-3.0
ν_μ CC Likelihood eff:	10.4%	25.2%	25.6%	11.1%	14.6%
NC Likelihood eff:	10.9%	22.1%	23.4%	24.6%	34.9%
ν_e Likelihood eff:	87.1%	80.8%	78.6%	72.6%	73.2%

FNAL (1MW)
Flux at 1300 km from target
Off-axis angle = 0.5°

$\delta = 0$
$\sin^2(2\theta_{13}) = 0.05$
Baseline = 1300 km

NC Bkg
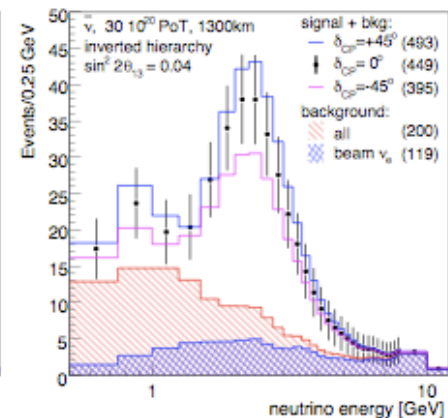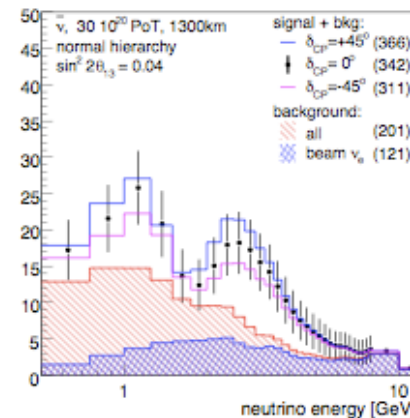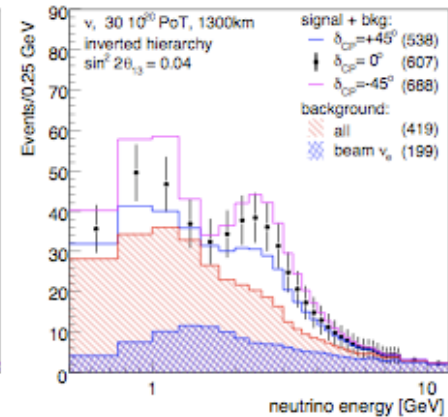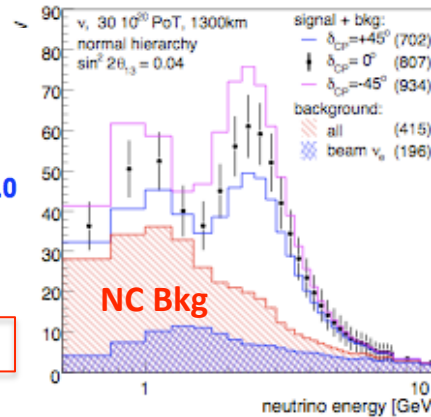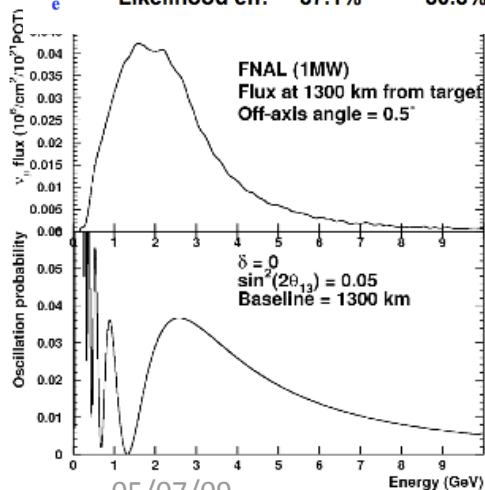
- Polfit doesn't work as well by itself above a few GeV. (gammas get close)
- F. Dafour combined it into a likelihood with other variables designed to remove background and was able to get good performance.

How much photo coverage?

We would like as much mass as possible, With as low a threshold as possible. More mass -> bigger cavern -> more PMTs for the same threshold. PMTs are a major cost driver.

Data: 1 GeV neutrinos from a beam

40%

KEK Beam direction marked by diamond

20%
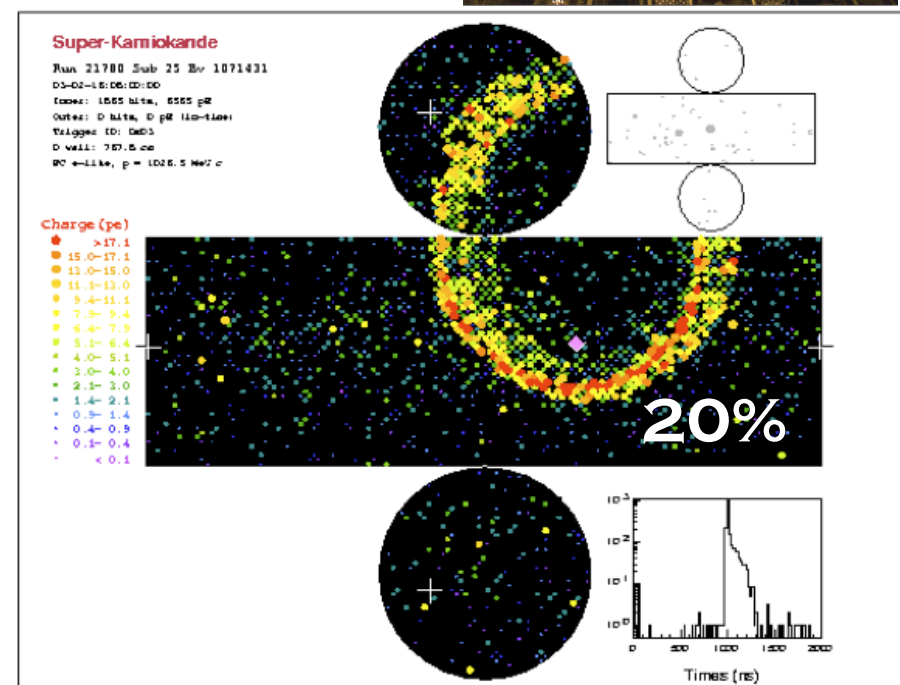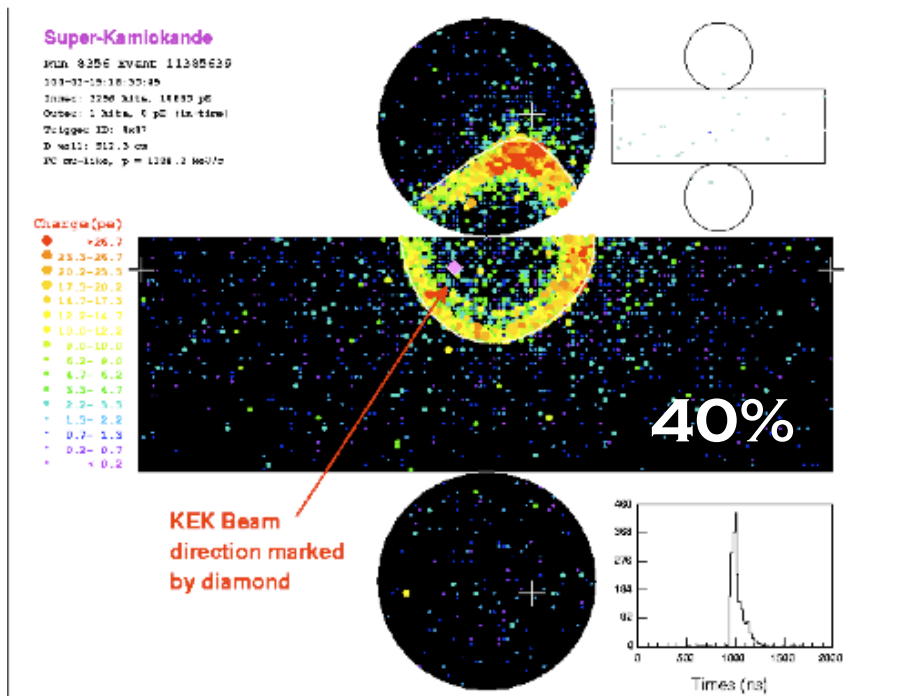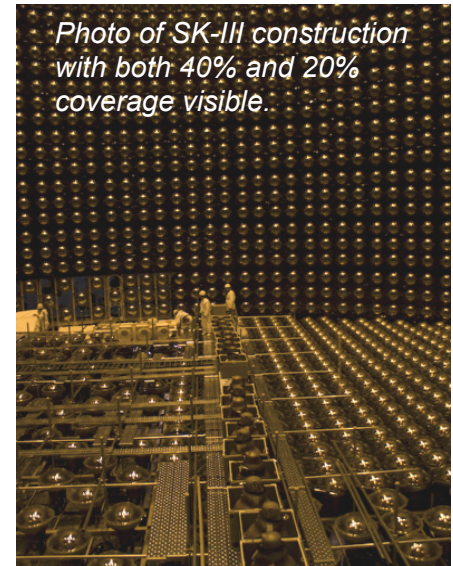
From SK/K2K experience: Fine for Beam!

PDK MC: Multi-ring, or less energy is harder
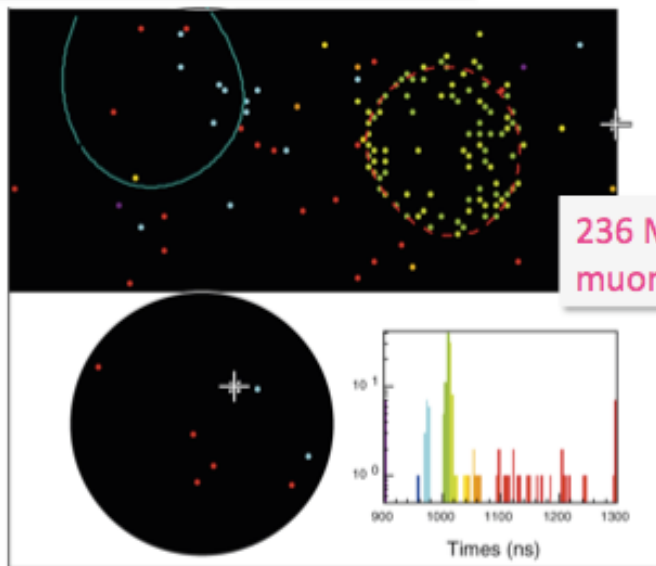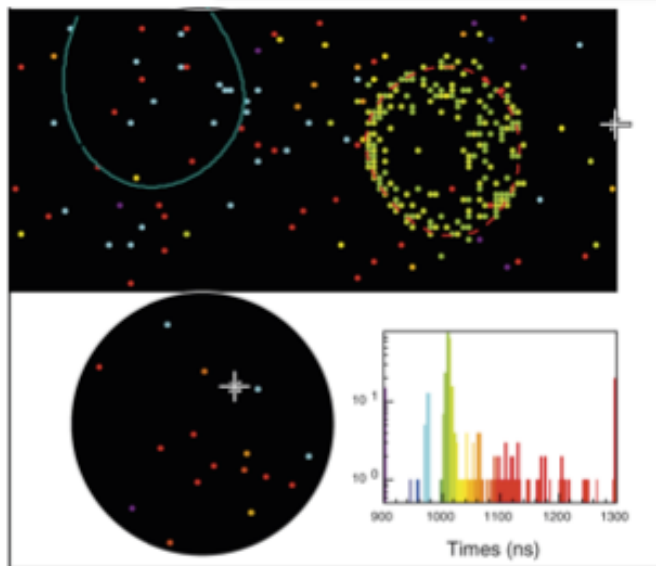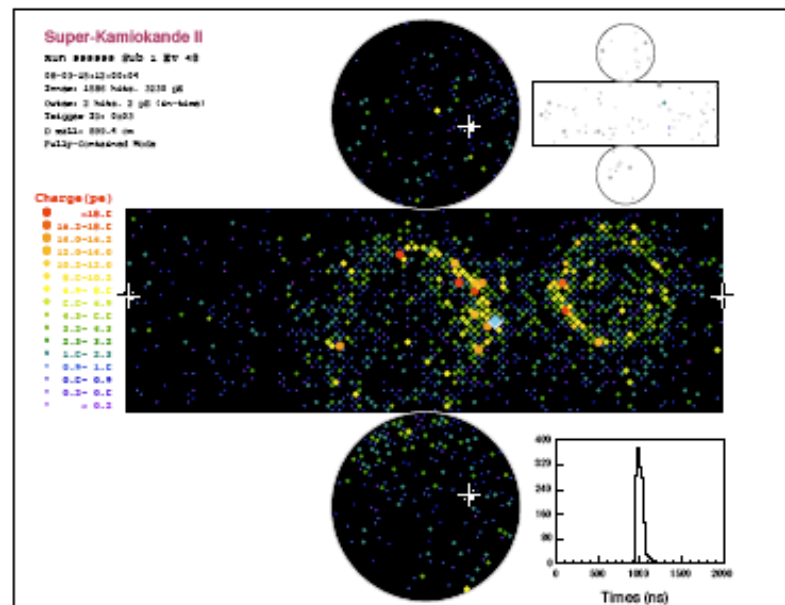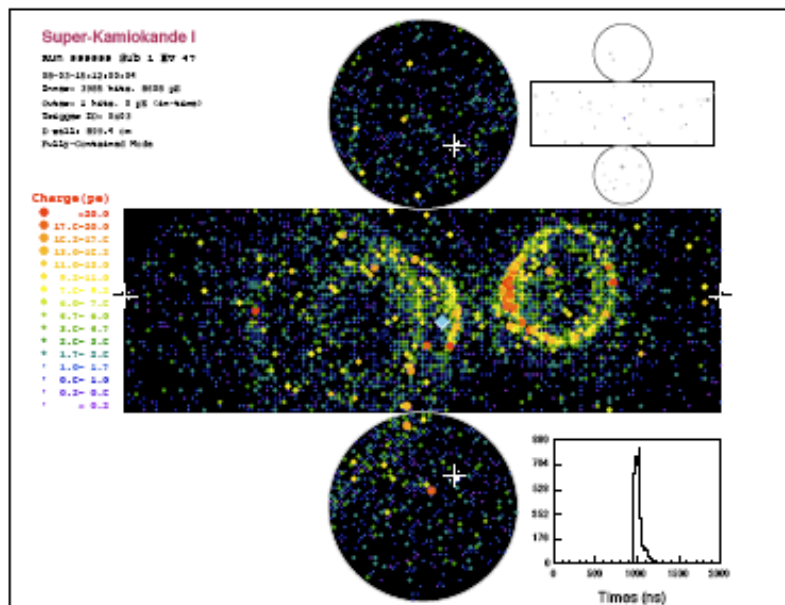
$$P \rightarrow e^+ \pi^0$$

Bkg and efficiency almost the same

236 MeV/c muon

Almost Same Bkg
Eff(20%)/Eff(40%) ~ .8
[Shiozawa NNN08]

$$P \rightarrow K^+ \nu$$

Can we put Gadolinium into the tank?

The anti-neutrino tag would allow us to search for and study:
• Supernova burst neutrinos
• **Relic Supernova neutrino flux**.
• Atmospheric Antineutrino tag (useful for hierarchy studies)

$\overline{\nu}_e$ p   n

Gd

e$^+$

γ
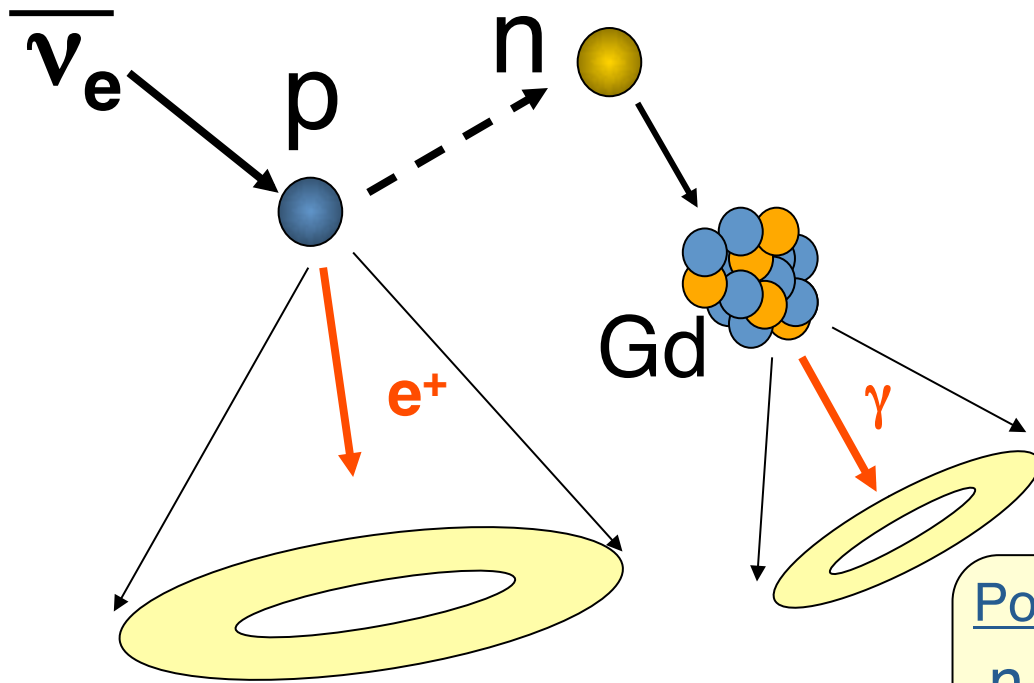
[reaction schematic by M. Nakahata]

Current R&D

•   Water purification system

•   Transparence / Material stability.

•   Design of a test tank at the Kamioka lab.

Possibility 2: 90% or more

n+Gd →~8MeV γ

ΔT = ~30 μsec

Hybrid Photodetectors (HPDs)
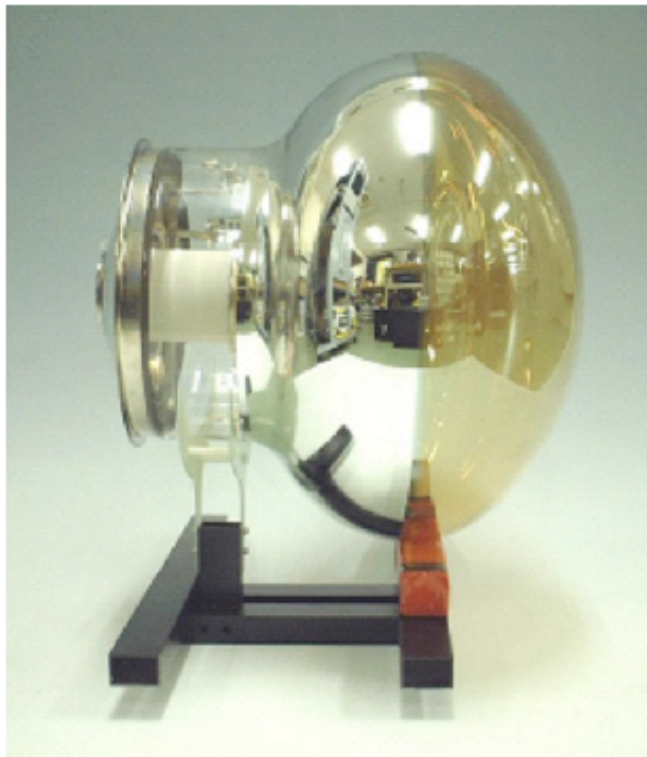
13inch HPD

Airhara group at the
Univerisity of Tokyo
With Hamamatsu
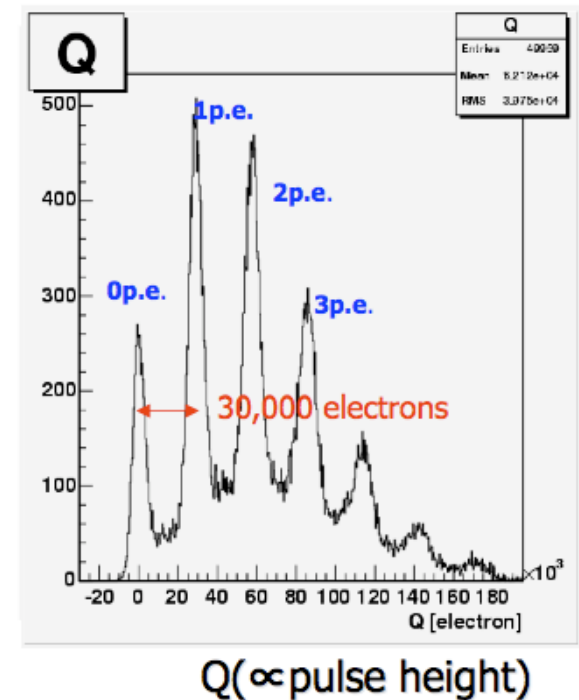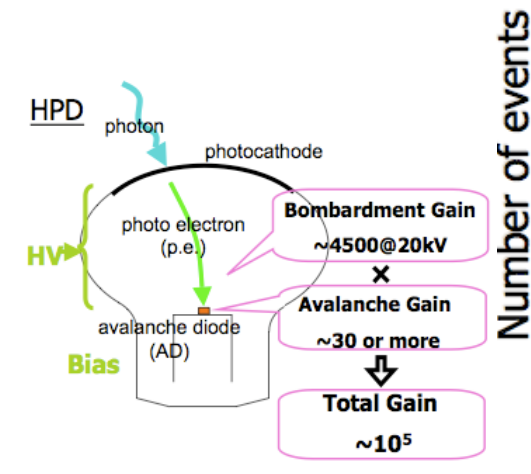
- No dynode structure
- High gain at first stage give very good single photon sensitivity.
- Fast (~1ns)
- Less gain (need good low noise preamps)
- Need ~20kV of HV

Picosecond Timing Project

http://psec.uchicago.edu/

Exploring the possibility of a cheap, large area, high resolution, fast photo-detector.

From

To

Window   Photocathode   MCP   Anode
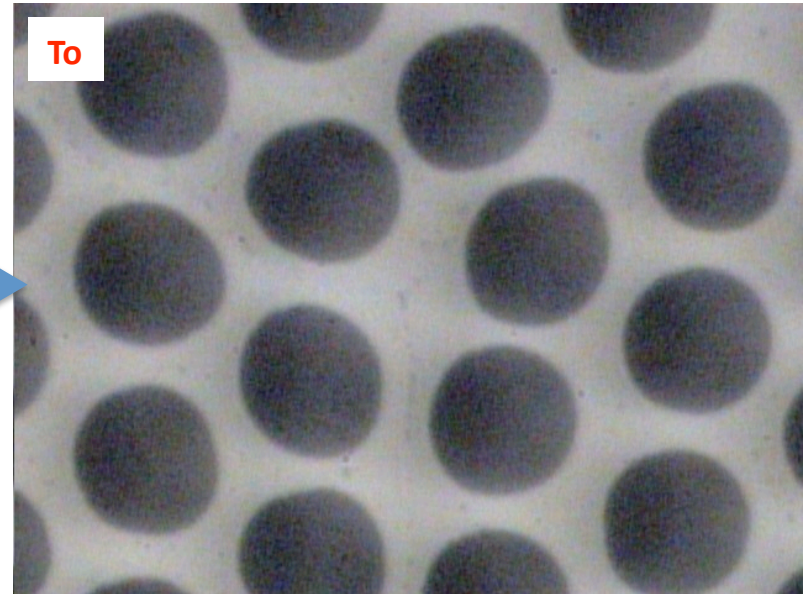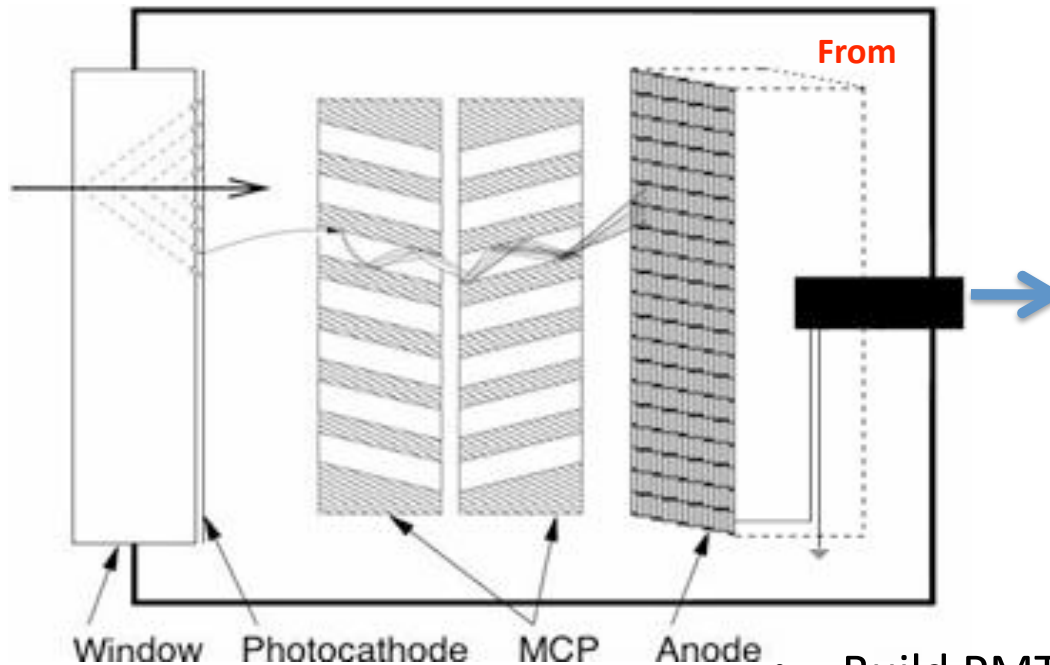
Henry Frisch and others at the University of Chicago / ANL / other universities, labs and companies.

- Build PMT structure into pores with dynode material defined in rings.

- Capacitively couple into transmission lines.

- Hope for cost-per-unit-area reduction to be competitive with PMTs for this application.

High Quantum efficiency tubes.

A. Karle, UW-Madison

- New high quantum efficiency 10" tubes are becoming available from Hamamatsu.

- These allow you to buy less tubes.

- IceCube has tested 78 new tubes (at -40C / 405nm) and saw an increase of 38% relative to the standard QE.
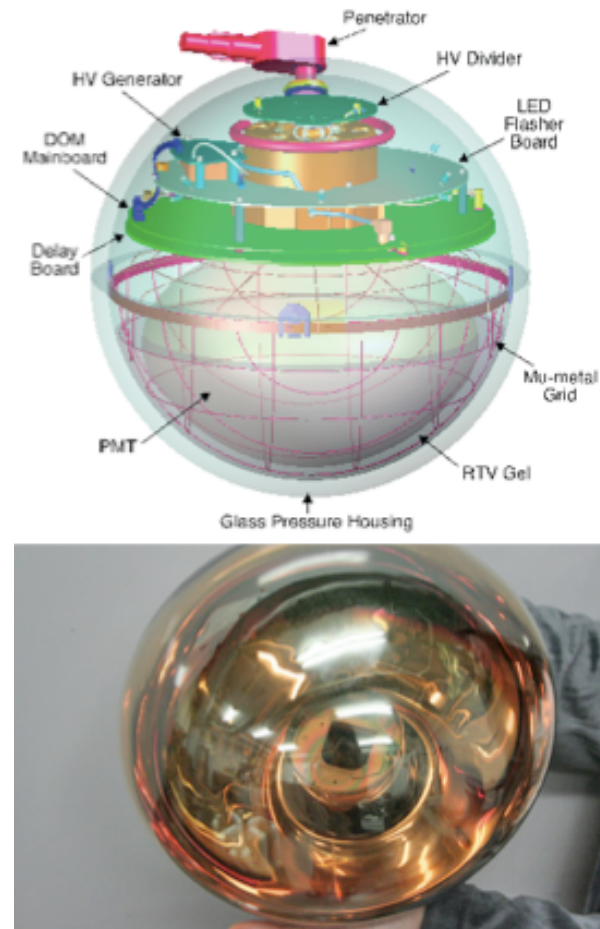
Power/ Cables

Orsay

PMm² : large photodection area *Ωmega*

PMm2" (2006 – 2009), funded by the
ANR : LAL, IPNO, LAPP and Photonis

eplace large PMTs (20") by groups of
smaller ones (12")

- central 16ch ASIC (PaRISROC)
- 12 bit charge + 12 bit time
- water-tight, common High Voltage
- Only one wire out (DATA + VCC)
- Target low cost
- Reuse many parts from MAROC &
  SPIROC

pplication : large water
Cerenkov neutrino
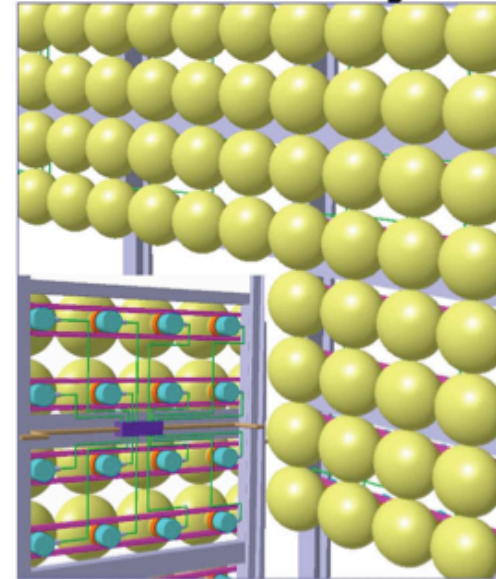
Orsay, 19 jan 2009   C. de La Taille - microelectronics at OMEGA-LAL   24

+ underwater electronics/HV distribution + wireless readout?

Liquid Argon TPC – An electronic bubble chamber

NC misidentified events: γ low energy 1

33 MeV

477 MeV

Vertex

350 MeV

Vertex

32 MeV

65 cm

$p \rightarrow K^+ \nu_e$

$P \approx 425~MeV$

Monte Carlo
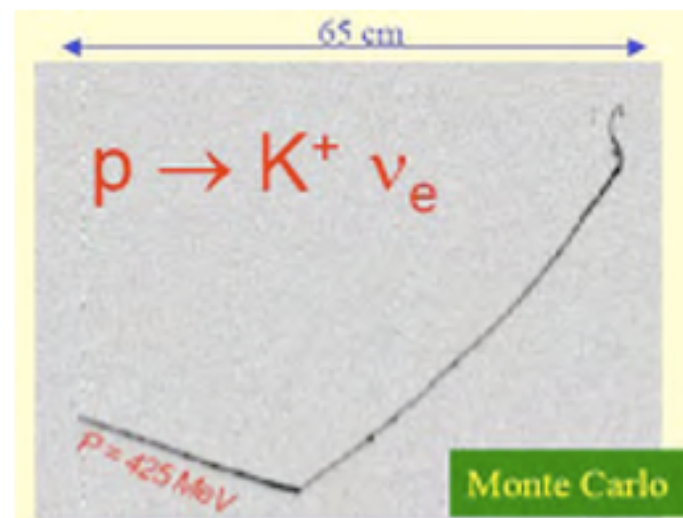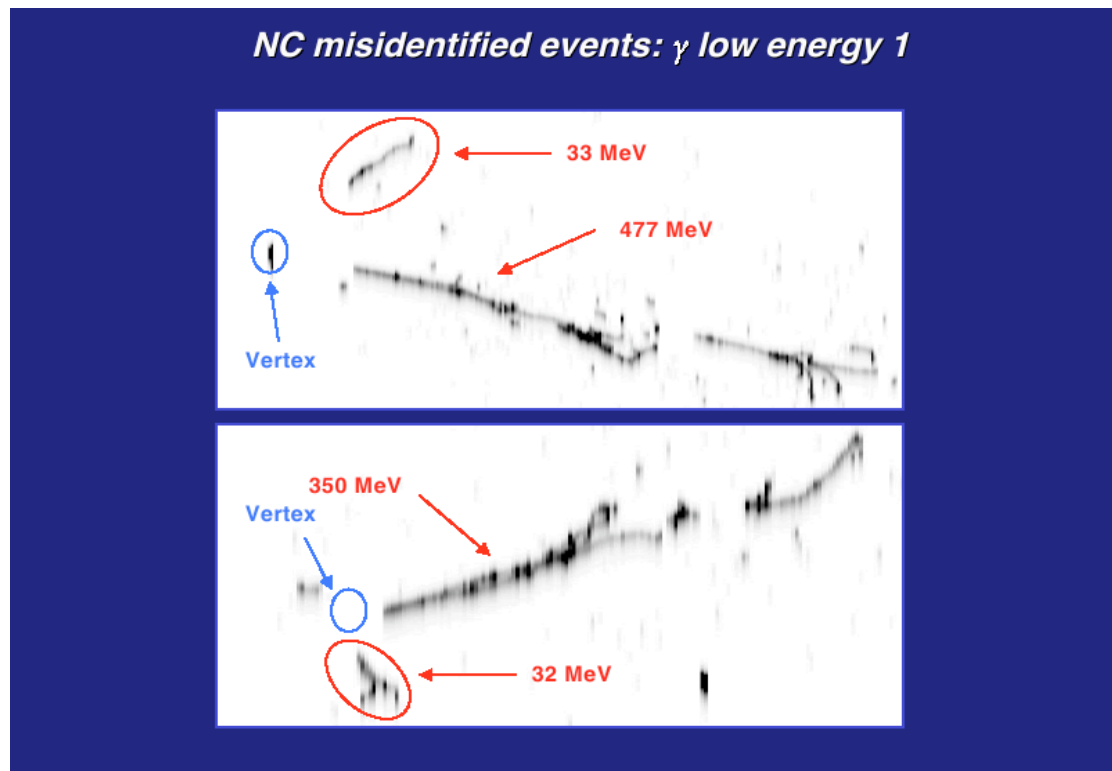
All particles are seen in LAR. In this proton decay the kaon would be below Cherenkov threshold.

Backgrounds missed in WC can be seen in LAR. Example from T2K 2KM studies: *Vectors of NC BG in a WC detector simulated in LAR.*

Resolution given by wire spacing ~ 3mm
(comparable to Gargamelle bubble size)

Liquid Argon Impact

NC Bkg gone!
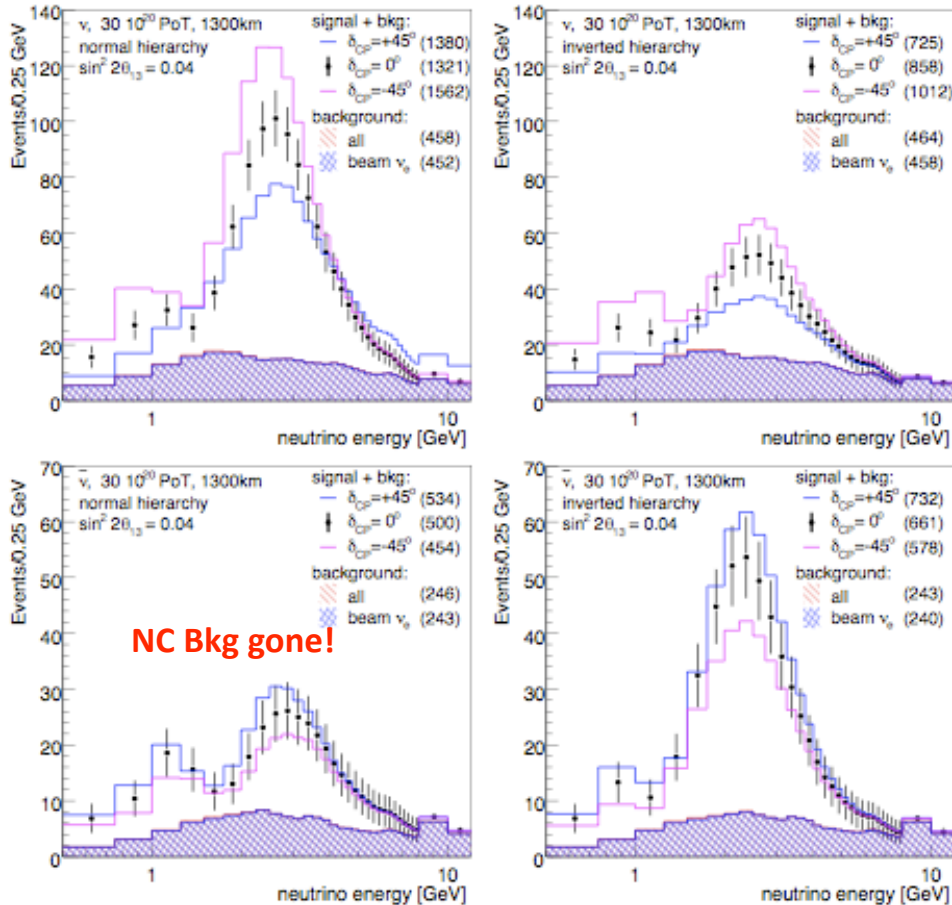
Studies suggest 100 kt LAR = 300kt WC

Nucleon Decay Limits
antilepton + meson
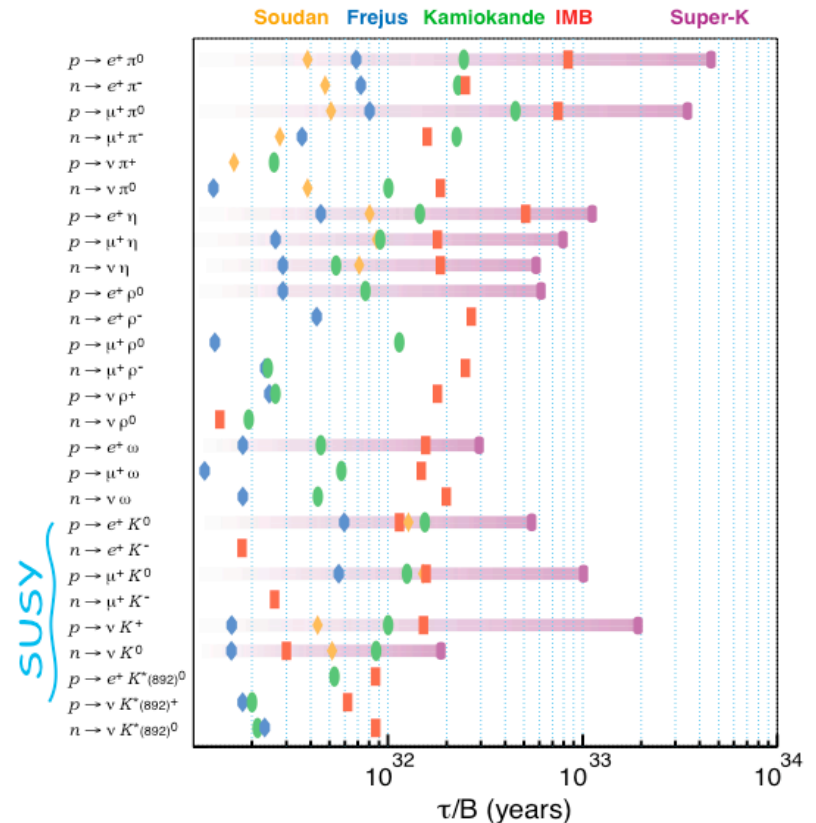
SUSY modes have Kaons.
LAR efficiency is ~ x6 WC

(Note: SK ~ 150 kton yr)
Go BIG to make a big improvement

Icarus Status

T600 Installation

June 2008

The ICARUS T600

1 - High Voltage Feedthrough
2 - Cathodes
3 - Field Shaping Electrodes
4 - Voltage degraders
5 - Electron drift Directions
6 - Readout Wire Chambers
7 - Inner Liquid Argon Vessel
8 - Thermal Insulation Panels
9 - Signal Feedthrough Chimneys

Electromagnetic shower

T300 2001

1.8 m

4.3 m

Wire

μ
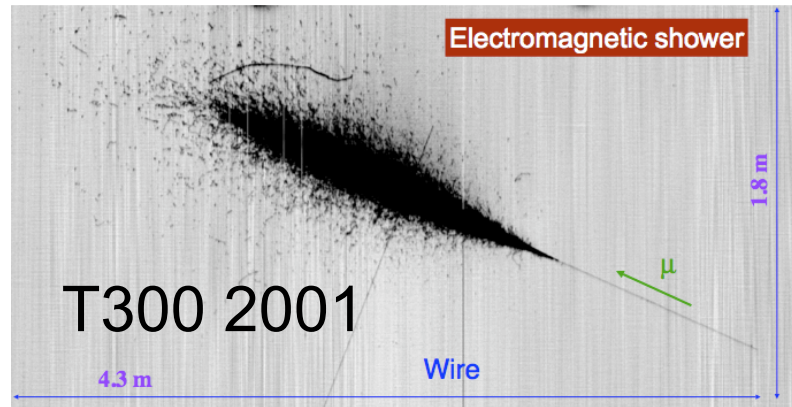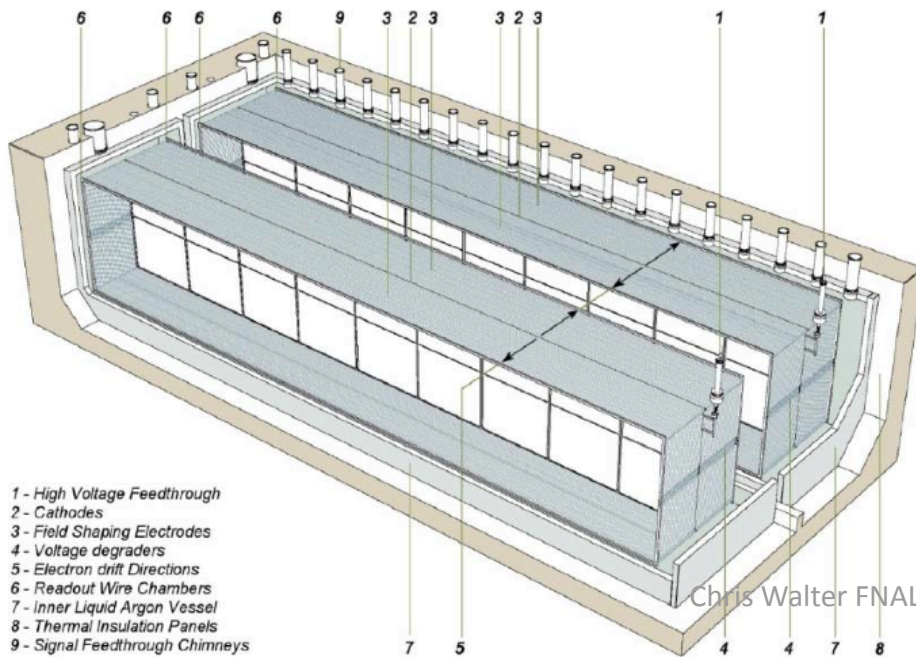
Staging in the US

Liquid Argon TPC R&D program in the US
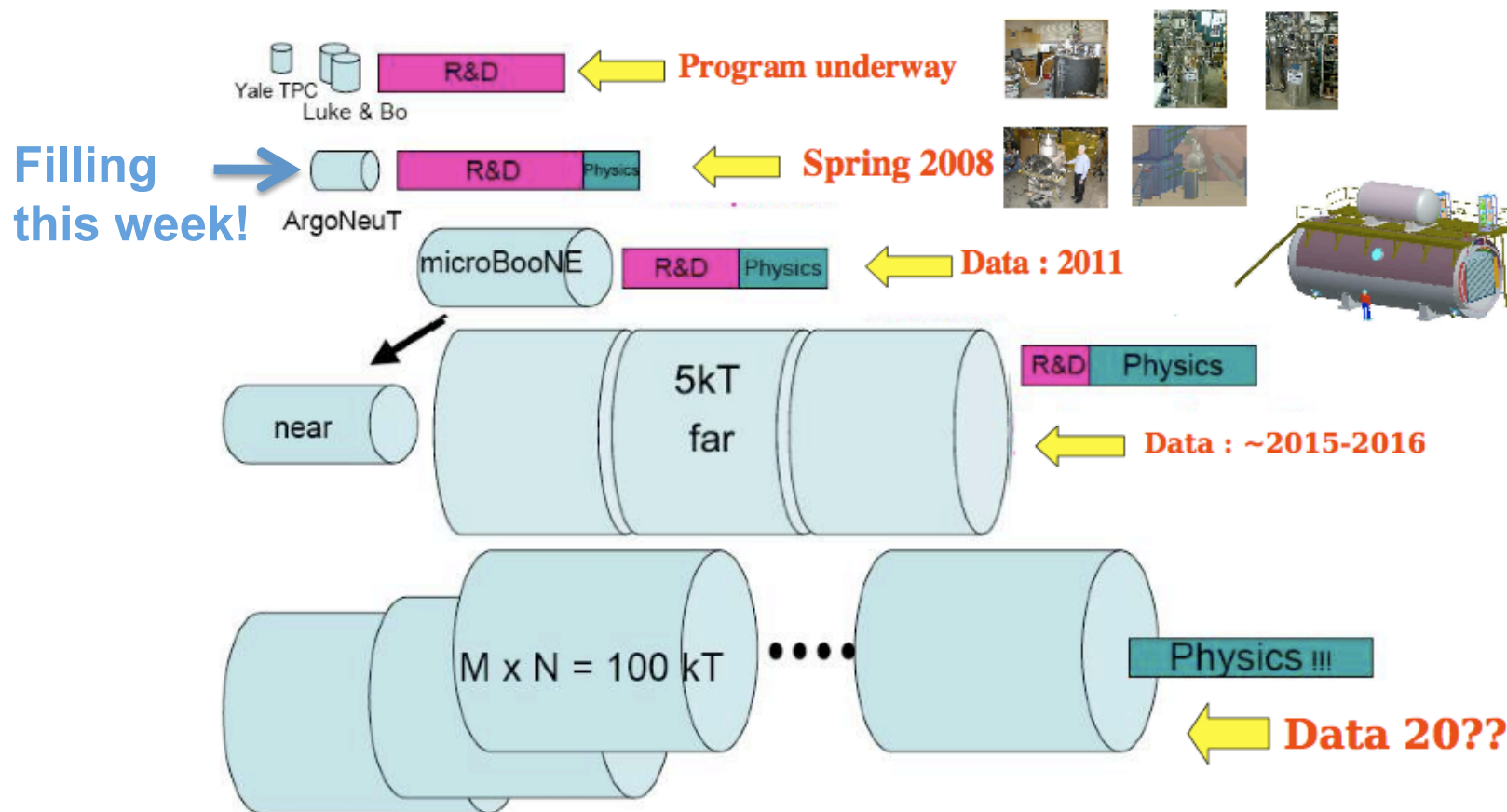
Bonnie Fleming @ HEPAP

Argoneut

FIRST ARGONEUT
EVENT
Aug. 9th, 2008

Collection View
240 wires

Time
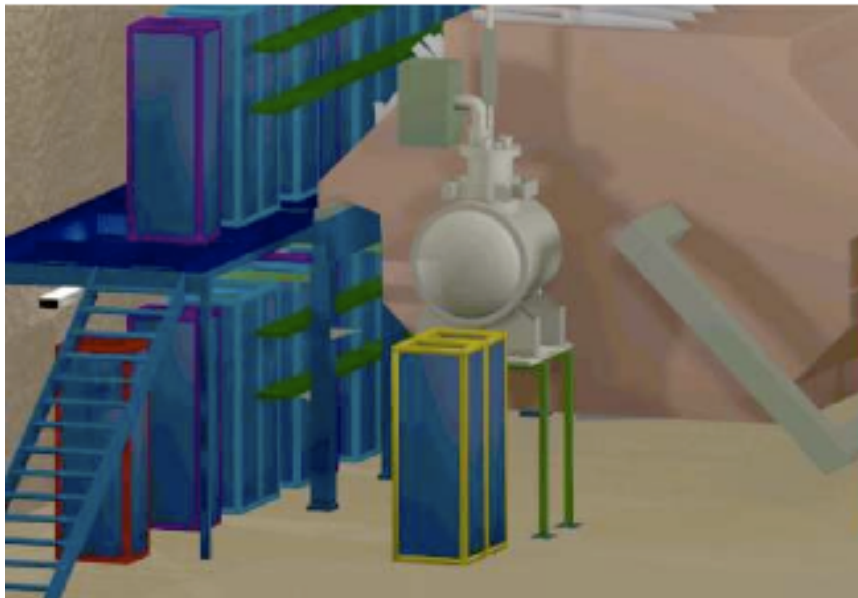
- .3 Tons / 500 Channels / ~ 150 events/ day
- Gain experience with long term underground running.
- Large sample for experience with reconstruction.

Microboone   ~ 2011

- Physics experiment to study the MiniBoone low-energy excess.
- Will study several R&D issues:
  - Purity of Ar in a cryostat without pumping down to vacuum first.
  - Low temperature CMOS based low-noise electronics inside of cryostat.

70 ton fiducial volume
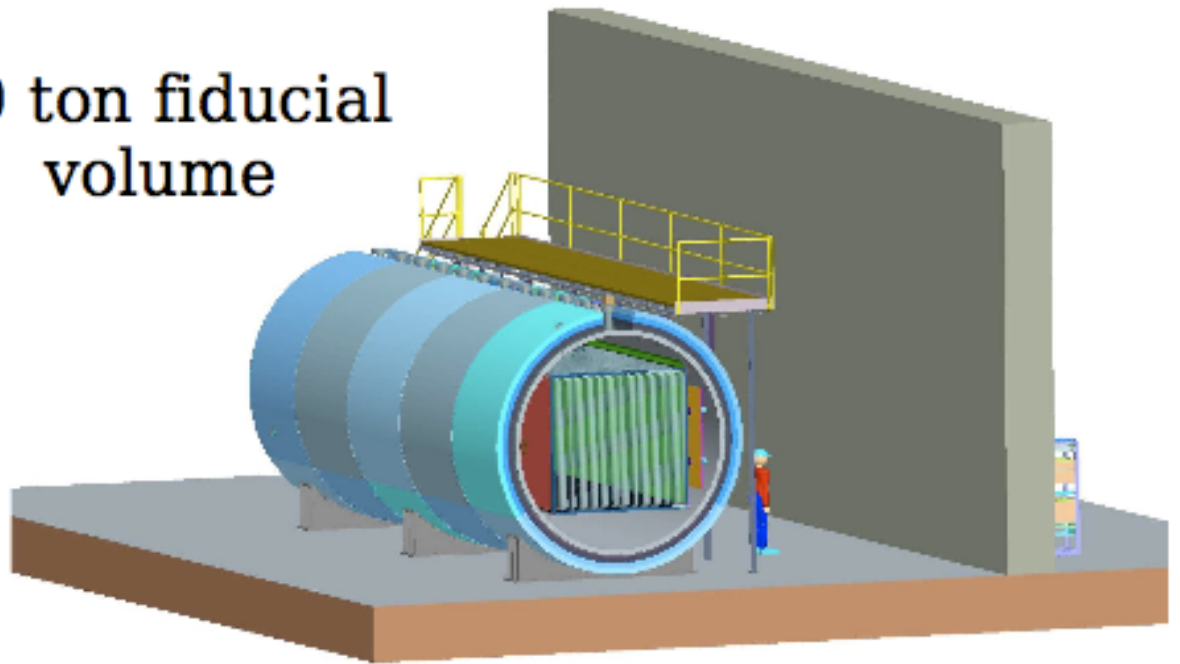
Drift length and Purity

As detectors get larger, the distance that the electrons can drift becomes critical.

FNAL now has a materials purity test stand.

Can check the effect of materials in the detector along with various purification schemes.
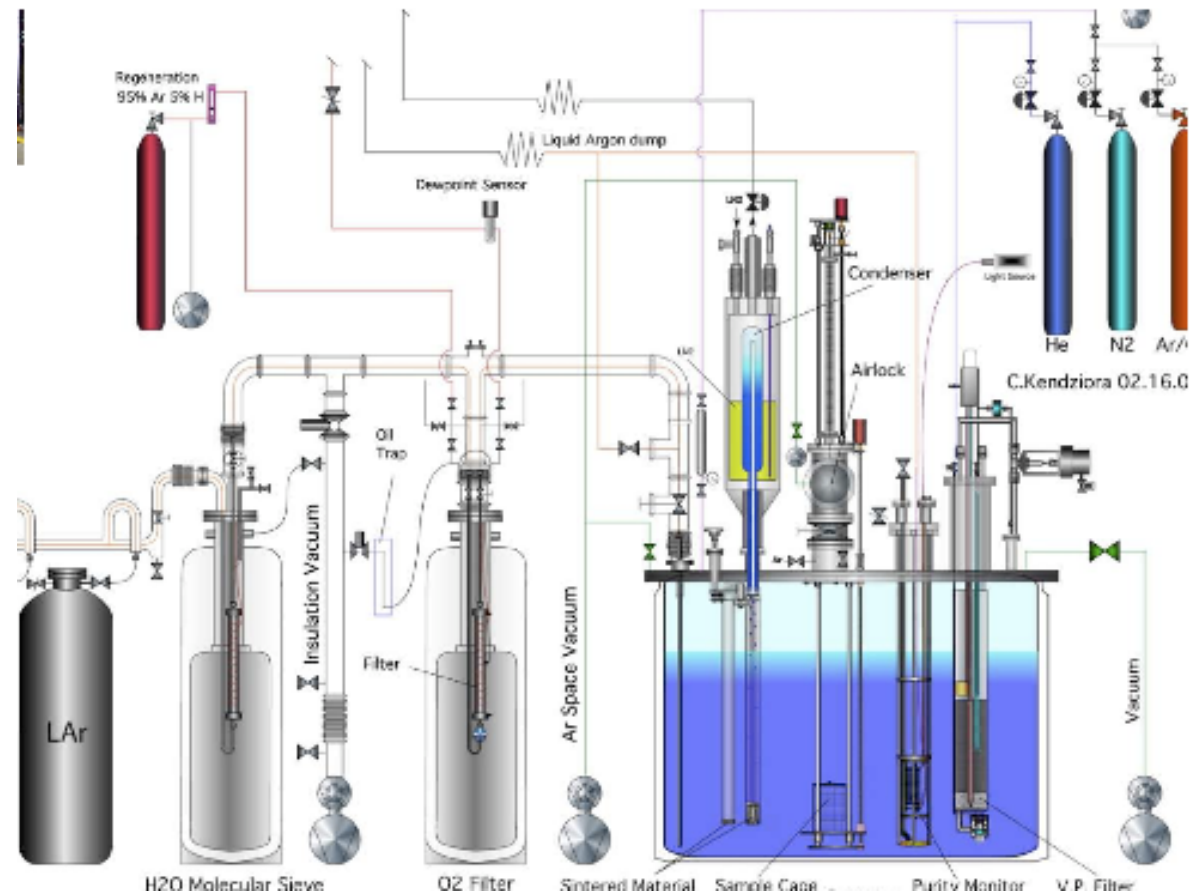
LAR at DUSEL?
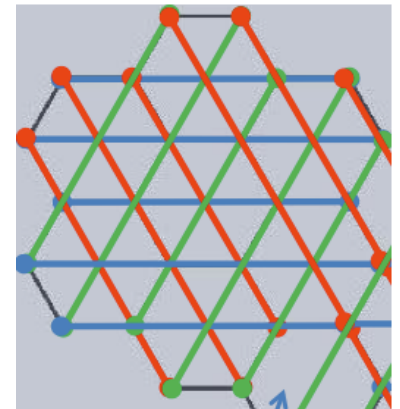
The plan is for a
Modular approach.
US group is now
Studying various options.
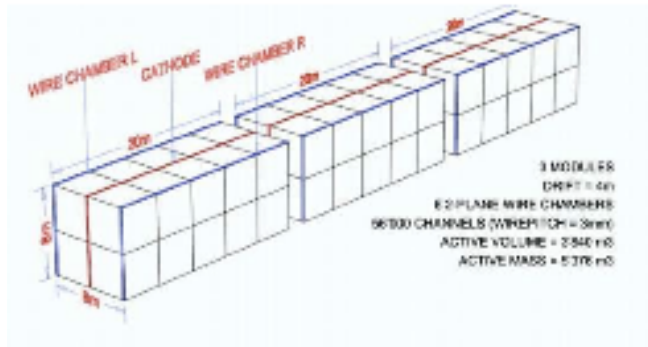
One Example

Details of a single test cell
100T Module

Only three unique parts:
Total 2048 parts

Hanguo Wang
UCLA

5kt liquid argon
TPC

H. Wang
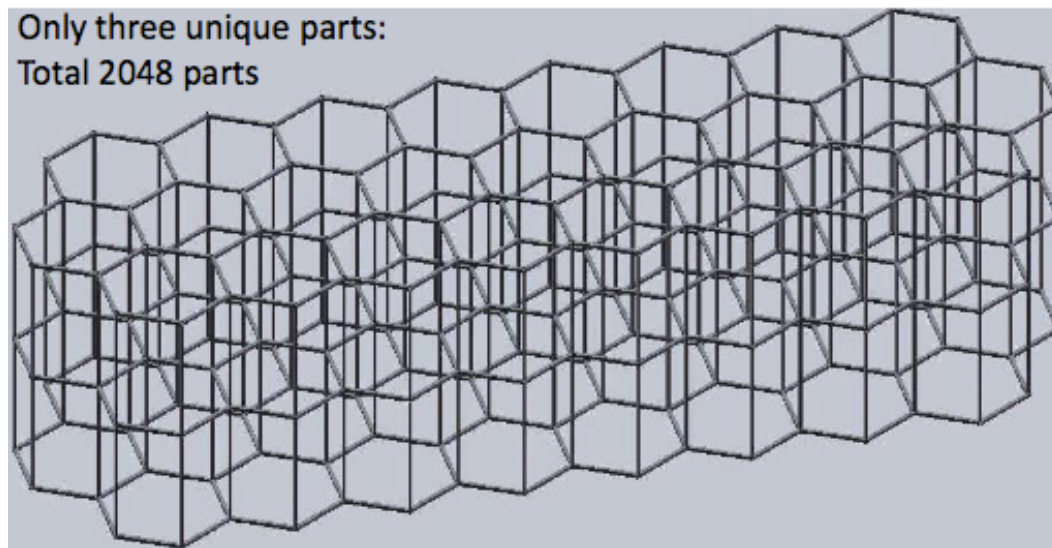
Chris Walter FNAL Extreme Beam Lecture
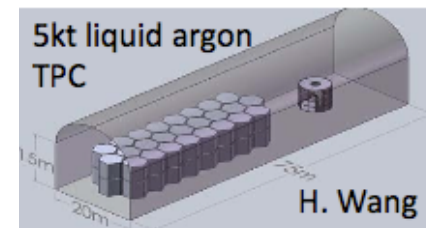
Glacier

A different approach: LNG tank based detectors.

Electronic crates

$d \approx 70\ m$

$h = 20\ m$

Perlite insulation

LNG tank

Charge readout plane

GAr

Electronic racks

Charge readout with extraction & amplification for long drifts

Low cost electronics

Extraction grid

LAr purification

E-field

LAr

$E \approx 1\ kV/cm$

Field shaping electrodes

Greinacher voltage multiplier up to MV

Cathode (- HV)

UV & Cerenkov light readout photosensors

Large area DUV sensitive photosensors

Andre Rubbia

Towards a large detector:

Small prototypes at KEK, Bern, ETHZ
Have shown LEM readout.
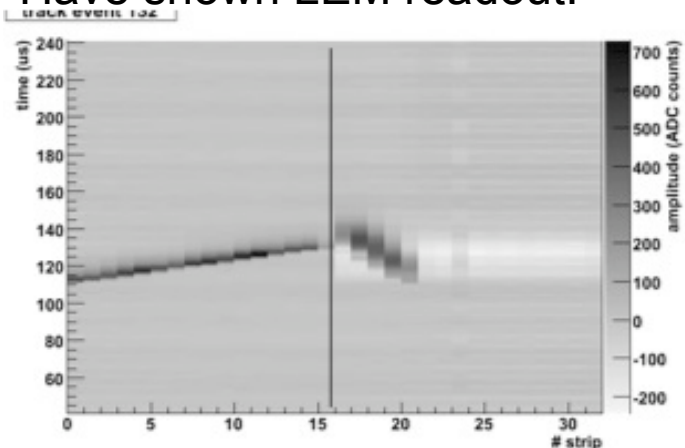
Unprocessed double LEM readout.

NOW: ArDm 1 ton prototype

Purification circuit

LAr Cooling circuit

Vacuum insulation

Detector

Field shapers

HV system

CuO cartridge (inside)

30 cm³ volume
Checkvalve
LAr-volume
Bellows
Piston
Flange
In coil engine Winten
Pneumatic chambers
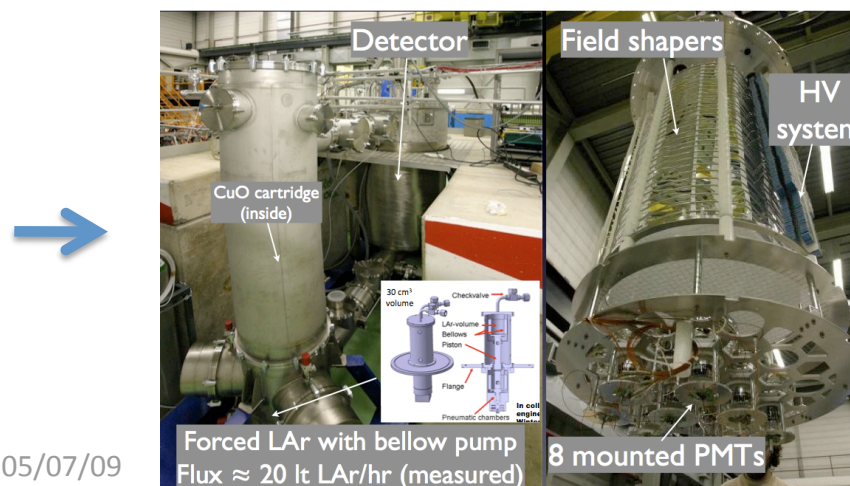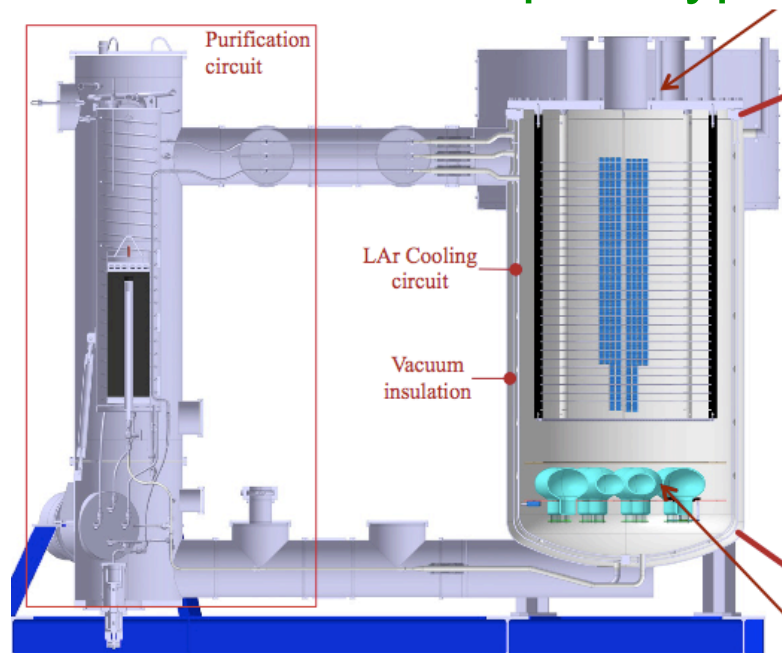
Forced LAr with bellow pump
Flux ≈ 20 lt LAr/hr (measured)

8 mounted PMTs

Filling now (1/2 full on 6th)
Test HV system upto 400kv
Instrument with LEMs by end of year

More R&D

- Leverages certified LNG tanks.

- No readout wires / Use LEM readout.

- Need very long drift path.

- Currently there is an active R&D program with Swiss/ France/Spain/Japan/UK

Next: proposed 3.9 ton beam test (in CERN North Area)
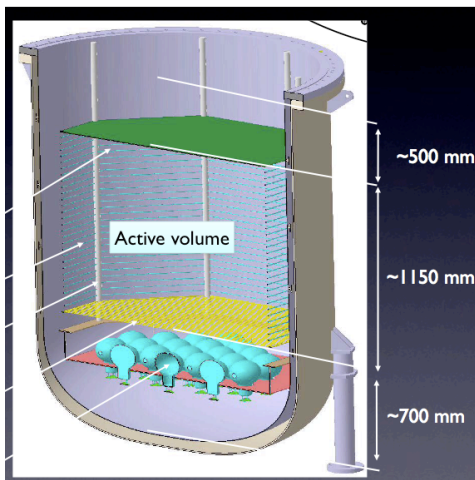
Next stage: 1kton engineering demonstration in neutrino beam.
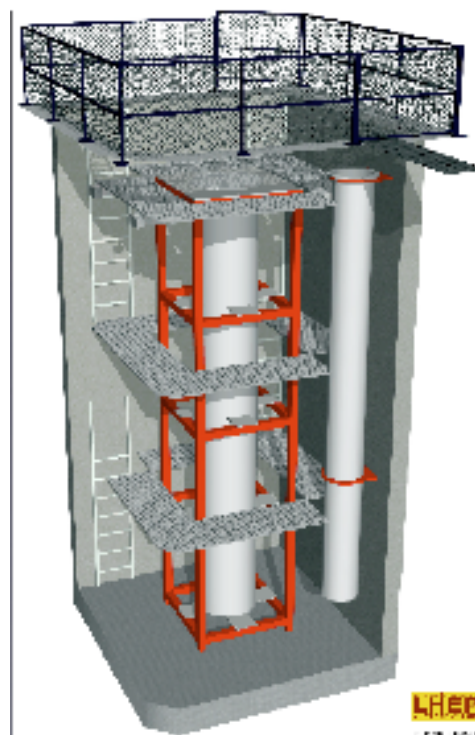
- Direct long drift measurement.

- Simulate 10-20 m drifts by reducing E field.

- High Voltage tests (~500Kv)

ARGOTUBE: external dewer / infrastructure ready. Inner detector in procurment phase.

Measuring oscillations with a neutrino factory.

Need sign measurement

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu \longrightarrow \mu^-$$

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

$$\overline{\nu}_\mu \rightarrow \mu^+$$
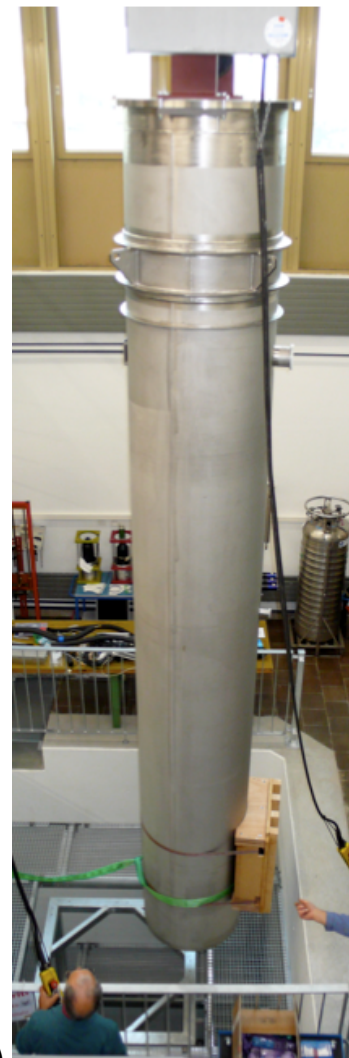
Golden Mode

$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e \longrightarrow e^+$$

$$\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$$

$$\nu_e \rightarrow e^-$$

Platinum Mode

CHECK OUT NuFACT!

ORPHANAGE of cast-off mascots

MIND

40m

14m

ν beam

50KT

14m

B=1 T

iron (4 cm) + scintillators (1cm)
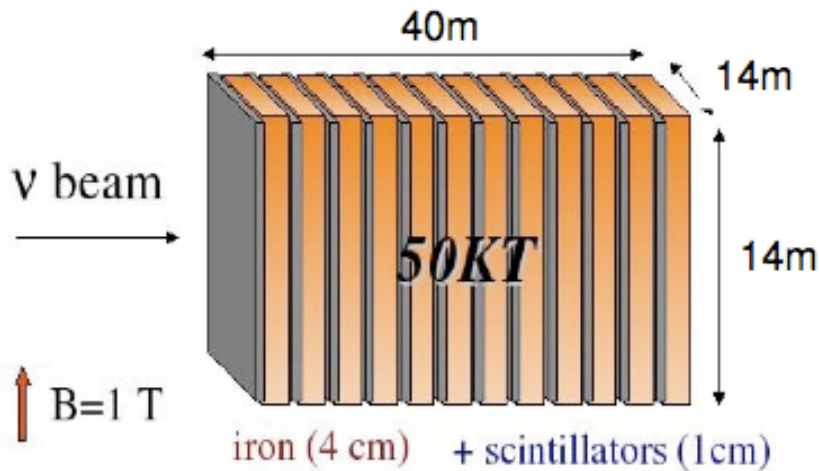
Detection of neutrinos in a massive MINOS like detector

Need muon mis-id at the 10^{-3} level
Current thinking: two 100kton modules at 4000 and 7500 km.

TASD

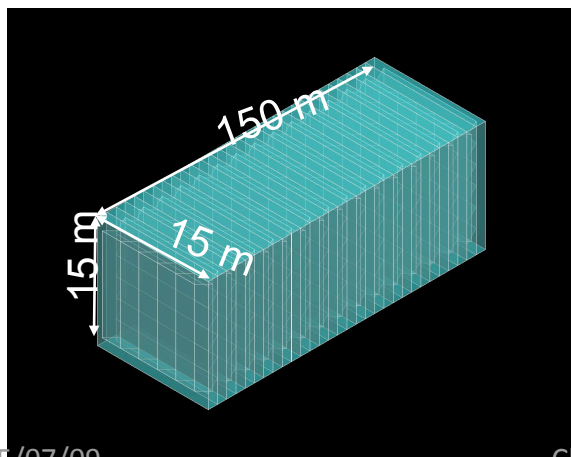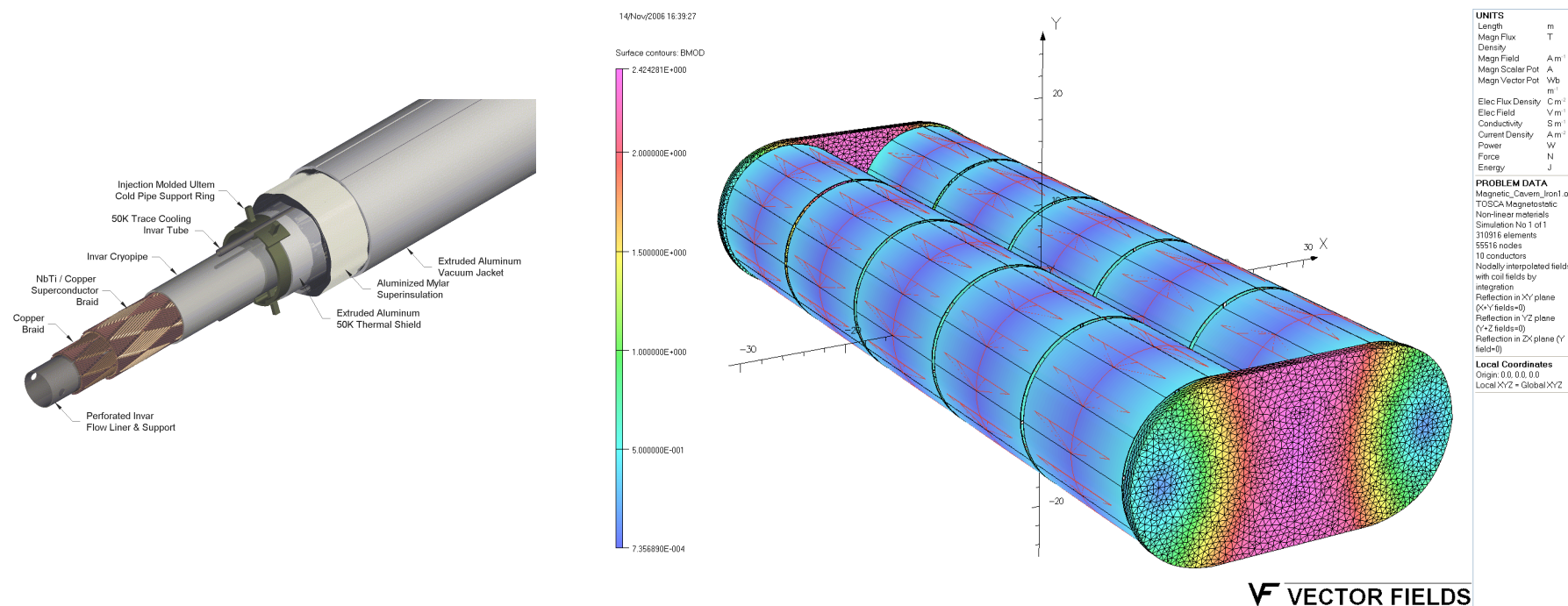150 m

15 m

15 m

A Nova like detector
With minerva like
Technology.
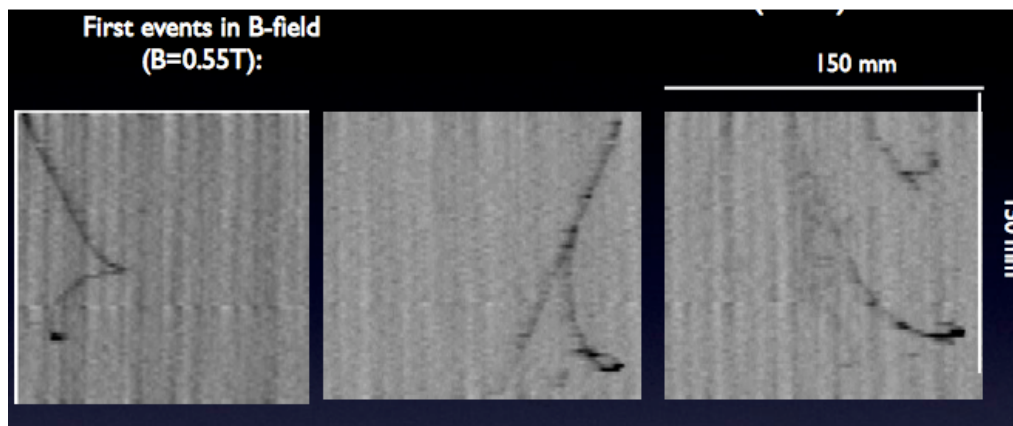For low-E NF ~ 35kton.

Wait! What about the sign?

Magnetize the hall?!

Make solenoid with VLHC
super-conducting Transmission Line.
(for a field strength of ½ T)

LAR or emulsion in a magnetic field?

Could a superconducting solenoid magnetize a large LAR detector?

First events in a B-Field (.55T)
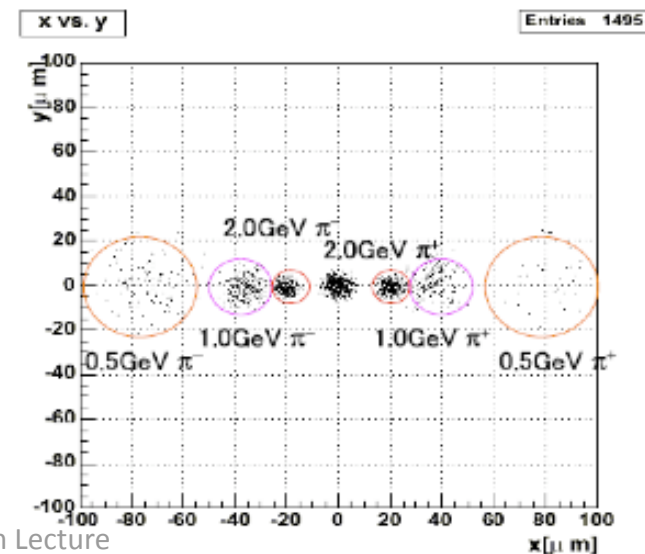New J.Phy.7 (2005) 63
NIM A 555 (2005) 294

What about an Magnetic Electronic Cloud Chamber (MECC)? This is emulsion in a magnetic field.

LAVINA NUFACT08

First pion beam test of MECC in B field.

(C. Fukushima, M. Kimura, S. Ogawa, H. Shibuya,
G. Takahashi, T. Hara and K. Kodama, paper in preparation)

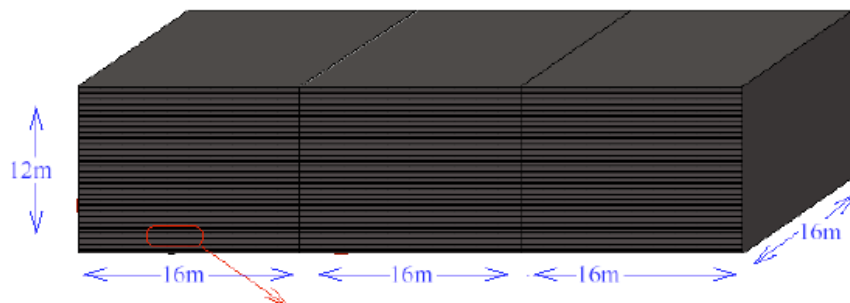# INO Experiment
(Steel and RPCs)

Goal: *A 50-100 kT detector with charge identification capability*

- **Two phase approach:**

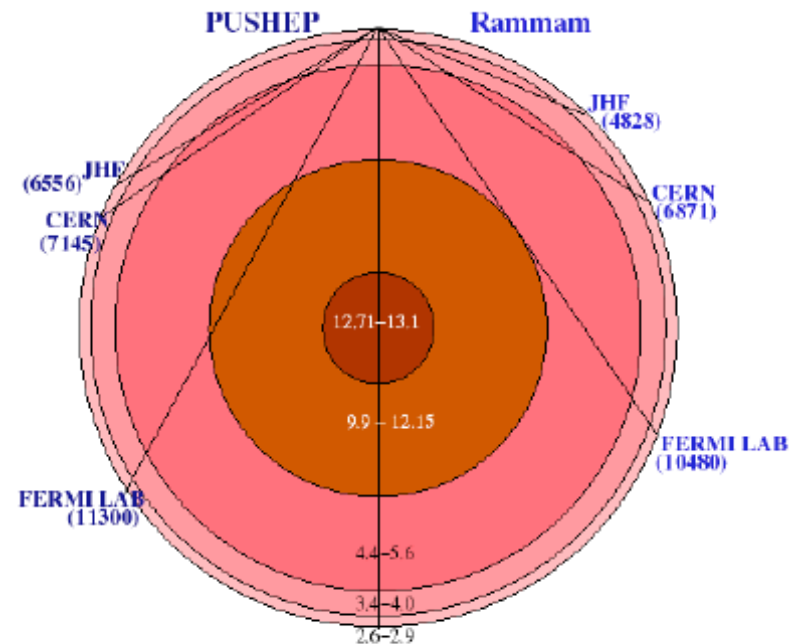**Operation of the Detector**

Phase I
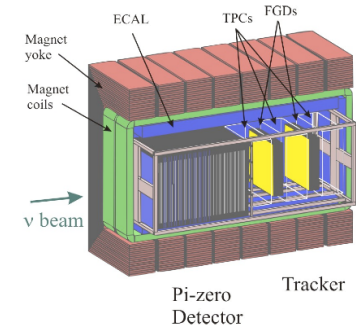**Physics with Atmospheric Neutrinos**
Phase II
Physics with Neutrino beam from a factory

- **Determination of θ_{13}**
- **Sign of Δm^2_{23}**
- **Probing CP violation in leptonic sector**

Near Detector Challenges

Building the near detectors needed for this high intensity environment will be a new important challenge. We will soon get important experience from Minerva and T2K.

- Need to measure flux, flavor composition and x-sections required for all oscillation analyses.
- This is a particular challenge where the far detector is water Cherenkov.
- The fluxes differ near to far and there are large x-section uncertainties for NC pion backgrounds.
- Anticipated backgrounds:
    - intrinsic ν_e
    - NC events which mimic intrinsic ν_e appearance such as single π^0 events
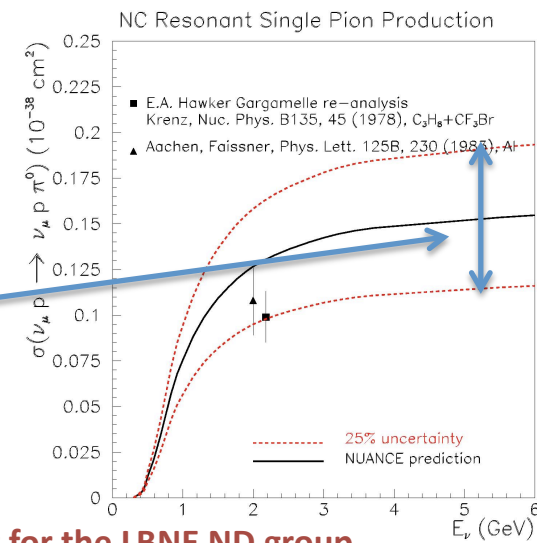
Far/Near Flux Ratio

(L=280m, R=2m, FD at 1297 km, ND at 1 km)

Preliminary
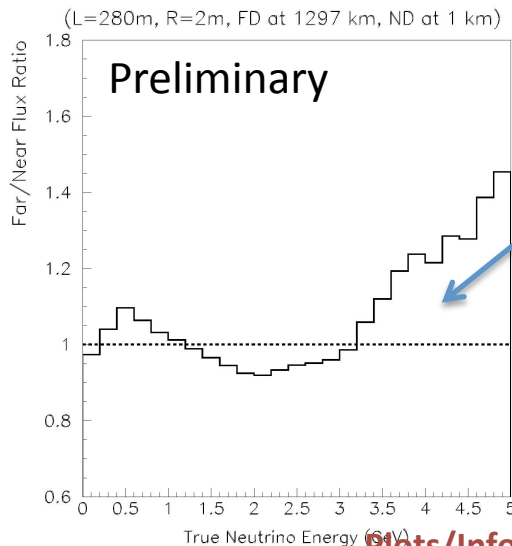
The high energy tail will generate NC interactions in the signal region.

Uncertainties are large.

NC Pion Production

NC Resonant Single Pion Production

- E.A. Hawker Gargamelle re-analysis Krenz, Nuc. Phys. B135, 45 (1978), $C_3H_8+CF_3Br$
- Aachen, Faissner, Phys. Lett. 125B, 230 (1983), Al

25% uncertainty
NUANCE prediction

Plots/Info from Sam Zeller / Christopher Mauger for the LBNE ND group.

Conclusion

- The next generation of experiments will be in the 100 – 500 kton range.

- Water and LAR are the two most probable choices at DUSEL.

- WC can be optimized for cost/physics topic

- LAR needs experience to scale up and choose a approach for giant detectors.

- In the longer term there may be even more difficult challenges.

- Remember proton decay and astrophysics!